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USING MARKOV DECISION MODELS AND RELATED TECHNIQUES

FOR PURPOSES OTHER THAN SIMPLE OPTIMIZATION II:

THE NORTHERN ANCHOVY, ENGRAULIS MORDAX

Roy Mendelssohn¹

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¹Southwest Fisheries Center, National Marine Fisheries Service,
NOAA, Honolulu, HI 96812.

I. INTRODUCTION

In part I (Mendelssohn 1978b), optimization techniques for stochastic models were used to analyze policy choices for salmon runs in Bristol Bay, Alaska. In that instance, stochastic models of the fishery were available, but no comparable policy analysis. Policies that optimized total expected (discounted) yield were found; policies that were optimal when year to year fluctuations had a cost were also found; and estimates of the risk entailed due to uncertainty about estimates of the model's parameters were also considered.

In this paper, similar techniques are used to improve upon an existing analysis, that of the northern anchovy, Engraulis mordax (MacCall 1978; Pacific Fishery Management Council 1978). Policies are found that improve upon present policies on almost every management criteria, whether the main objective be biological (total harvest), economic (total expected discounted value of the catch), protection of the stock, or being certain that the industry is not shut down often and needlessly. Further, it is shown that the policy that maximizes the total harvest does not close the fishery 2 out of 3 years, as stated in the Pacific anchovy management plan (Pacific Fishery Management Council 1978). Finally, the optimal policies can be explained in terms of the underlying assumptions of the model used. This allows the decisionmaker to decide how much weight to give the results of the model, depending on how realistic he or she feels these critical assumptions are.

Two points should be emphasized at the outset. The present policies are based on a thoughtful look at past experience, and an insightful look at what were thought to be sound alternative policies. The problem arises in that these policies are selected on an ad hoc basis, and our intuition on stochastic models is not always as we would believe. The present paper improves upon this analysis by optimizing, for any given objective, over all possible decision rules. It is this fact that makes possible the finding of policies that are improvements on every criteria.

Secondly, the results presented here show how to improve upon the policy analysis for anchovy, but do not necessarily imply that the present management schemes, all things being considered, are not more acceptable. This seeming contradiction arises because a model's main purpose is insight; the actual decision process includes many factors not included in the model. These factors include balancing political pressures from the different interest groups, biological and economic intuition or insights gain from experience with the fishery, and the similarity with past management policies. The latter point is particularly important, for it is often difficult to implement radically different management schemes, and decisionmakers often feel "safer" (less risky) with "the devil they know," rather than the devil they don't know.

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II. THE MODEL

The model used was developed by MacCall (1978) and is also described in detail in the Pacific anchovy management plan (Pacific Fishery Management Council 1978). Let x_t be the biomass at the start of period t , F_t the fishing effort during period t , and d_t a random variable that is independent and identically distributed through time. Then in general form the model is:

$$x_{t+1} = s[x_t, F_t, d_t]$$

where $s[\cdot, \cdot, \cdot]$ is given by:

$$s[x_t, F_t, d_t] = x_t e^{-(F_t + 0.8)} + \left(e^{d_t \left(\frac{1}{3.649} + \left(\frac{1}{x_t} - \frac{1}{3.649} \right) 0.695 \right) - 1} - x_t e^{-(0.8)} \right) e^{-0.152 F_t} \quad (2.1)$$

where d_t is distributed as $N(0, 0.2294)$. This can be simplified somewhat by noting that:

$$\left(\frac{1}{3.649} + \left(\frac{1}{x_t} - \frac{1}{3.649} \right) 0.695 \right) - 1 = \frac{3.649 x_t}{\frac{0.695}{3.649} + 0.305 x_t}$$

The transition has a deterministic term for mortality in the present biomass, and a stochastic term for larval recruitment to the fishery.

Catch, therefore, is a random variable also, given by:

$$C_t = \frac{F_t}{F_t + 0.8} x_t \left(1 - e^{-(F_t + 0.8)} \right) + 0.647 \left(e^{d_t \left(\frac{3.649 x_t}{0.190 + 0.305 x_t} \right)} - x_t e^{-0.8} \right) x \frac{0.76 F_t}{0.76 F_t + 0.8} \left(1 - e^{-(0.152 F_t + 0.16)} \right) \quad (2.2)$$

To set this up in a manageable form for numerical work, four things need to be decided:

- (i) an objective function,
- (ii) the decision variable, and any constraints on its value,
- (iii) a grid over which to discretize the problem,
- (iv) a methodology to redefine the problem over the discrete grid.

For (i), two objective functions are used throughout. The first maximizes the expected total discounted harvest. More formally, if E is the expectation operator, the objective is to:

$$\text{maximize } E \sum_{t=1}^{\infty} \alpha^{t-1} C_t \quad 0 \leq \alpha < 1 \quad (2.3)$$

where C_t is the random variable catch, and the system satisfies all the constraints in (2.1) and (2.2). If $\alpha = 1$, the equivalent criterion is to maximize the expected per period harvest, or

$$\text{maximize } \lim_{T \rightarrow \infty} E \left(\frac{\sum_{t=1}^T C_t}{T} \right)$$

Economic considerations are taken into account more explicitly, by using a one-period return of:

$$V(C_t, x_t) = (59.67 \times C_t) - (1.8953 \times 10^{-5} \times C_t^2) - (10315 \times C_t \times x_t^{-0.4}) \quad (2.4)$$

so that the objective is to maximize the expected total discounted economic value

$$\text{maximize } E \sum_{t=1}^{\infty} \alpha^{t-1} V(C_t, x_t) \quad (2.5)$$

The derivation of $V(C_t, x_t)$ is given in full detail in the Pacific anchovy management plan (Pacific Fishery Management Council 1978). However, it bears closer examination. For fixed x_t , $V(\cdot; x_t)$ is concave in C_t . Therefore, taking the partial derivative with respect to C_t :

$$V^{[1]}(C_t, x_t) = 59.67 - (3.7906 \times 10^{-5} \times C_t) - (10315 \times x_t^{-0.4})$$

It can readily be seen that for $x \leq 392,900.8661$ this function achieves its maximum at zero, where it has a value of zero. This states, however indirectly, that the industry prefers being shut down if the population size is too small, and that it has no fixed costs when shut down. As will be seen, many of the optimal policies exploit the fact that the industry faces zero costs when not harvesting.

For each run, the stationary distribution of the Markov chain induced by an optimal policy is calculated. This makes it possible to calculate the average catch per period, its variance and standard deviation, the median population size and catch, and the percent time the population is less than a given amount. The latter is particularly important in that recreational fishers have come out in favor of no commercial fishing if the population falls below 1 million tons. Thus the percentage of time there is no fishing can be calculated. It will be seen that this "cutoff," per se, does not by itself accomplish what appears to be the true goal of the recreationalists, that is to keep the probability that the population is less than 1 million tons at an acceptable level.

For (ii), there are two possible decision variable, catch or effort. In the Pacific anchovy management plan catch is used (Pacific Fishery Management Council 1978). Here, effort is the decision variable. The reason for this is that catch is a random variable. Thus, any observed catch could have come from an almost infinite combination of values of F_t and d_t . However, the value of F_t is needed to calculate the transition probabilities. It is not clear in MacCall (1978) and the Pacific anchovy management plan (Pacific Fishery Management Council 1978), how the iterative procedure described finds the value of F_t . On the other hand, F_t is a deterministic variable in the model; and, once given an optimal policy, it is easy to calculate the expected catch in a period for any combination of x_t and F_t .

A more important problem is what bounds should be put on F_t ? Clearly, $F_t \geq 0$. However, at the present time the fishers do not have the capacity for unlimited effort. The analysis of an expected catch quota will be very different if it is assumed that the entire quota is taken compared with an analysis where it is assumed that only part of the quota is taken. However, information does not exist to determine which of these is the actual case. To look at this problem, runs were done with successively increasing upper bounds on F_t . These runs were analyzed for two things: where the policy no longer changed as the bound increased; and where the expected catch from most population sizes became much larger than anything ever caught before. Upper bounds of 0.1, 0.2, 0.4, and 0.6 were tried. It will be seen that a constraint of the form $0 \leq F_t \leq 0.1$ or $0 \leq F_t \leq 0.2$ seems to be the most realistic.

Also, to examine the effects of limiting harvests if the population size is less than 1 million tons, identical runs were done where $F_t \equiv 0$ if $x_t \leq 1$ million tons.

A grid size of 50 equally spaced points between 0.073 and 3.649 was used. Previous computational experience (Mendelssohn 1978a) suggests that a 50-100 point grid is necessary to insure numerical accuracy, particularly when calculating the tail probabilities of the stationary distribution. Using 3.649 as an upper bound (actually all states ≥ 3.649 are put into this state) is a conservative procedure, in that it rules out infrequent but very large "potlatches" that would occur otherwise. This makes it less desirable to allow the population to get very large; lowers the estimate of the mean catch; and overestimates the probability of being in the lower population sizes. Thus, if the policies are an improvement in each of these categories, we can feel safe that the grid choice, if anything, made it more difficult to obtain improvements.

Equation (2.1) was discretized as follows. Let Φ be the standard normal integral. From (2.1):

$$\Pr\{x_{t+1} \leq \omega\} = \Pr\{s[x_t, F_t, d_t] \leq \omega\} = \Pr\left\{d \leq \ln(a(x_t))\right\}$$

where $a(x_t)$ is given by equation (2.1).

Then from the normality of d :

$$\Pr\left\{d \leq \ln(a)\right\} = \Phi\left(\frac{\ln(a)}{\sigma}\right)$$

where $\sigma = 0.479$. Let x_1, x_2 be two adjacent points on the grid.

For any F_t ,

$$\Pr\left\{x_{t+1} \leq x_2 \mid x_t, F_t\right\} = \Phi\left(\frac{\ln a(x_2)}{\sigma}\right) - \Phi\left(\frac{\ln a(x_1)}{\sigma}\right)$$

that is, the total probability of going to any state in the interval $(x_1, x_2]$. The mathematics and convergence issues of this procedure are discussed in Bertsekas (1975) and Whitt (1978); note that this procedure is different from that used in MacCall (1978) and the Pacific anchovy management plan (Pacific Fishery Management Council 1978), where point densities are used, and then are normalized by dividing through by the sum of the probabilities.

The point estimate of expected catch is used. (It would be a worthwhile effort to repeat this analysis trying differing returns--for example, averaging the returns aggregated into any state-action pair, as in Mendelssohn 1978a.) This is calculated by noting that the random variable enters into (2.2) at only one spot:

$$0.647 (e^d) \frac{3.649 x_t}{0.190 + 0.305 x_t}$$

It is well known that if $d \sim N(m, \sigma^2)$, then e^d is a lognormal random variable with mean $\exp\left\{m + \frac{1}{2} \sigma^2\right\}$. Therefore, the expected catch is:

$$\frac{F_t}{F_t + 0.8} x_t \left(1 - e^{-(F_t + 0.8)} \right) + 0.647 \left(1.1216 \left(\frac{3.649 x_t}{0.190 + 0.305 x_t} \right) - x_t C^{-(0.8)} \right) \\ \times \frac{0.76 F_t}{0.76 F_t + 0.8} \left(1 - e^{-(0.152 F_t + 0.16)} \right)$$

All runs are solved using dynamic programming, using several techniques to accelerate convergence and eliminate actions (Porteus 1971; Hastings and van Nunen 1977). It is well known that if the one-period return is a random variable, then the solution to (2.3) or (2.4) is the limiting solution to the following system of recursive equations:

$$f_0(\cdot) \equiv 0 \tag{2.6}$$

$$f_n(x) = \max_{0 \leq F \leq F_{\max}} \left\{ G(x, F) + \alpha E f_{n-1}(s[x, F, d]) \right\}$$

where $G(x, F)$ is the expected one-period return.

III. RESULTS

A total of 17 runs were performed, each with a discount factor of $\alpha = 0.97$. This is in the range of discount factors that would arise if it is assumed that the true interest rate is the present interest rate less the rate of inflation. Test runs were performed for discount factors ranging from 0.95 to 0.99, with little change in the results. The results are summarized in Tables 1(a-p). In the latter tables, for each state, optimal effort is given, the

expected one-period catch is given, and the cumulative percent of time (in the long run) the population is less than or equal to the given state is also given. At the end, summary statistics of each run are given.

As mentioned before, it is difficult to compare these runs with present options in terms of mean catch per period, and its variance, because if larger effort is allowed, these figures will increase. Instead, we will see that policies have been found that produce expected catches as large as if not much larger than anything the commercial fishery has caught to date, at the same time producing population statistics that improve upon the present policies in every category.

The first question is, which of the runs is the correct model? In the 6-year period 1970-76, the commercial fishery had catches of 96,242; 44,853; 69,100; 132,636; 82,817, and 158,511 tons. A look at Tables 1(c and d) show that this is well within the range of catches if $F_{\max} = 0.1$. In fact, at that maximum fishing effort, the mean catch is roughly 176,500 tons and the median catch is 174,000 tons, assuming the United States gets it all. However, Mexico is building up its reduction fishery, and cooperative management is the goal. This may mean the United States would be allotted only 50%-70% of the catch for a given year. If the United States would get only 70% of the catch, this is still a reasonable model, because roughly 40% of the time the expected yearly catch would be greater than any previous United States catch.

If the United States retains only 50% of the catch, then $F_{\max} = 0.1$ would be restrictive on growth in either the United States or the growing Mexican fishery. However, if $F_{\max} = 0.2$, then even if the United States were to get only 50% of the expected catch each year, Tables 1(e-h) predict roughly 50% of the time the expected catch to the United States would be higher than any previous catch, and 25% of the time the expected United States catch would be 50% greater than any previous catch.

Thus, in terms of actually modeling the present fishery $F_{\max} = 0.1$ or 0.2 appears to be the most realistic assumption. The other runs show what might be expected if there is unlimited growth in fishing capacity, be it from the United States or from Mexico.

Let $F_{\max} = 0.2$. Two runs were performed with no other restrictions on the fishery, one with expected total discounted harvest as the objective, and the other with expected total discounted economic value as the objective. These are summarized in Tables 1 (e and g). As mentioned earlier, both optimal policies, even assuming the United States gets only 50% of the expected catch each year, produce catches well in excess of the largest amount yet caught by the United States commercial fishery.

When expected total discounted harvest is the criterion, an optimal policy has no catch only 1.07% of the time, and the population size is less than 0.5 million tons 3.3% of the time, and less than

Table 2

1 million tons only 17.13% of the time. These compare more than favorably with any policy given in the Pacific anchovy management plan (Pacific Fishery Management Council 1978) (see Table 2 for the comparable statistics). When expected total discounted economic value is the criterion, there is no fishery only 8.8% of the time, and the population is less than 0.5 million tons only 1.97% of the time, and less than 1.0 million tons only 14.72% of the time. Again these statistics improve upon every comparable statistic in the Pacific anchovy management plan, while allowing for expansion in the total fishery.

Comparable statistics are given in Tables 1 (b-d) assuming that $F_{\max} = 0.1$. Again, each optimal policy improves upon any of the comparable policies in the Pacific anchovy management plan. The question then is what is gained by not allowing harvesting for population sizes less than 1 million tons or less than 0.5 million tons. The latter is examined in Table 1 (d), and the only major difference is the increase in the percent years there is no fishery.

Tables 1 (f and h) give comparable runs to the two discussed previously, except now if the population size is less than 1 million tons, no harvesting is allowed. What is noticeable is that particularly when expected total discounted economic value is the criterion, little or no change occurs in the percent time the population is less than 1 million tons, but the percent time there is no fishery increases dramatically. To achieve a reduction in the percent time the fishery is less than 1 million tons requires either a cutoff point greater than a million tons and a concomitant increase in the number of years there is no fishery, or else a decrease in the fishing effort, which has the effect of limiting industry expansion.

The remaining runs show the probable effect of allowing a much larger commercial fishery. There are four noticeable trends when following an optimal policy.

Firstly, as the mean catch per period increase, so does the variance, the percent time there is no fishery, and the percent time the population is less than 1 million tons.

Secondly, an optimal policy for the expected total discounted value does not change as $F_{\max}$ increases above 0.4. This implies, that according to the model, unless economic conditions change, the industry will not want to expand beyond this point.

Thirdly, adding the "cutoff" at 1 million tons does not produce much of a change in the percent time the population is less than 1 million tons, while it always increases significantly the percent time there is no harvest.

Finally, for runs where the objective is to maximize expected total discounted economic return, no harvesting occurs at population sizes less than 876,000 tons, which is not very different than the avowed position of the recreationalists.

IV. DISCUSSION

More important than finding optimal policies is to discover why the particular policies found are optimal, and what this says about the strength and weaknesses of the model. The first consideration is when "amount harvested" is the only consideration, why is the fishery fished so hard? The second question is, why, even with

economic considerations included, is it optimal not to fish with ever increasing frequency as maximum fishing effort increases? And finally, why doesn't a cutoff produce the desired result of protecting the stock?

The first question, and to some extent the last question, can be answered by examining more closely equation (2.1). Note again, there is a deterministic part representing mortality of present biomass, and a random part representing recruitment which only depends on biomass at the beginning of the period. Even with no fishing, in 1 year 55% of the present biomass dies, and in 2 years 80% of the standing biomass dies. Since recruitment, according to the model, only depends on biomass levels at the beginning of the period, the "discounted" value (discounted by mortality) of a ton of biomass is quite low. If it isn't harvested now, it will pretty much be dead anyway, and will add little additional to the recruitment 2 years hence. Thus, it is desirable to harvest hard. Cutoffs do not protect the stock, because the recruitment next year, which is a large part of the population, only depends on the population size before harvesting.

The answer to the second question has already been alluded to in section II. There it is shown that the one-period economic return function is such that at certain biomasses the return will be negative if harvesting commences, but zero if there is no harvesting. Clearly, however, there is a cost to the industry from not harvesting; in fact, there is probably a cost if the catch is below

a certain minimum level; all of which would make it more desirable from the industry's point of view, to harvest a small amount rather than none. When the model does not specify such "smoothing costs" (or fixed costs, or start-up and shutdown costs) an optimal policy will not be concerned with how frequently no fishing occurs. And this is reflected in the policies found here, as well as the present policies discussed in the Pacific anchovy management plan (Pacific Fishery Management Council 1978).

Finally, we have already answered partially the third question. But more importantly, the question remains is a "cutoff" the underlying aim of the recreationalist? Probably not. More than likely, what they desire is to keep the probability that the fishery is less than 1 million tons at acceptable levels, whether it be by "cutoff," reduction of fishing effort, or whatever.

All models represent restrictions and abstractions of reality, and these shortcomings should be guides to use and not reason for dismissal. Given the results in section III, and the present capacity of fishery, good policies can be found that allow for expansion in the fishery, almost never have no fishing, and have a smaller chance for low population sizes than present policies. However, if the fishery expands to a point where maximum fishing effort is greater than 0.2, it will be important to do two things. First, to more properly evaluate the impact on industry, fixed costs and "smoothing costs" should be researched, to include the real costs faced by industry if there is no harvest.

From the recreationalist point of view, the stochastic dynamic program (2.6) can be optimized subject to a constraint on the long-run probability of having a standing biomass less than 1 million tons. This constraint can parametrically be made tighter and tighter, so that the tradeoff between this constraint and the value of the fishery can be examined. Details can be found in Mendelssohn (1977).

Finally, all the policies considered depend on knowing the standing biomass each year. This can be a costly undertaking. How much would be lost if the estimate were obtained only every 2 years, or 3 years, as compared to the savings from not obtaining the estimate? How should an optimal policy be modified to take into consideration this decrease in information about (or increase in risk in) the system? These questions will be examined in a future paper.

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Table 1 (a).--Base case--no harvesting allowed.

State	Stationary distribution
0.073	0.0000
0.146	0.0001
0.219	0.0005
0.292	0.0014
0.365	0.0031
0.438	0.0057
0.511	0.0094
0.584	0.0143
0.657	0.0205
0.730	0.0280
0.803	0.0368
0.876	0.0468
0.949	0.0580
1.022	0.0740
1.095	0.0839
1.168	0.0984
1.241	0.1138
1.314	0.1301
1.387	0.1472
1.460	0.1649
1.533	0.1832
1.606	0.2020
1.679	0.2213
1.752	0.2409
1.824	0.2608
1.897	0.2808
1.970	0.3010
2.043	0.3212
2.116	0.3414
2.189	0.3615
2.262	0.3814

Table 1 (a).--Continued.

State	Stationary distribution
2.335	0.4012
2.408	0.4207
2.481	0.4400
2.554	0.4590
2.627	0.4776
2.700	0.4959
2.773	0.5138
2.846	0.5313
2.919	0.5484
2.992	0.5651
3.065	0.5813
3.138	0.5971
3.211	0.6124
3.284	0.6273
3.357	0.6417
3.430	0.6557
3.503	0.6692
3.576	0.6823
<u>>3.649</u>	1.0000

Median population = 2.700

% time population is ≤ 0.5 = 0.57%

% time population is ≤ 1.0 = 5.8%

Table 1 (b).--Total discounted harvest, effort restricted to be
no greater than 0.1.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0000
0.146	0.100	0.011	0.0004
0.219	0.100	0.017	0.0018
0.292	0.100	0.023	0.0046
0.365	0.100	0.028	0.0092
0.438	0.100	0.034	0.0156
0.511	0.100	0.039	0.0239
0.584	0.100	0.045	0.0340
0.657	0.100	0.051	0.0457
0.730	0.100	0.056	0.0590
0.803	0.100	0.062	0.0737
0.876	0.100	0.067	0.0897
0.949	0.100	0.073	0.1069
1.022	0.100	0.078	0.1251
1.095	0.100	0.084	0.1441
1.168	0.100	0.089	0.1638
1.241	0.100	0.094	0.1841
1.314	0.100	0.100	0.2049
1.387	0.100	0.105	0.2261
1.460	0.100	0.111	0.2476
1.533	0.100	0.116	0.2692
1.606	0.100	0.121	0.2909
1.679	0.100	0.127	0.3126
1.752	0.100	0.132	0.3342
1.824	0.100	0.137	0.3557
1.897	0.100	0.143	0.3770
1.970	0.100	0.148	0.3980
2.043	0.100	0.153	0.4187
2.116	0.100	0.158	0.4391
2.189	0.100	0.164	0.4591

Table 1 (b).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.262	0.100	0.169	0.4787
2.335	0.100	0.174	0.4979
2.408	0.100	0.179	0.5167
2.481	0.100	0.185	0.5350
2.554	0.100	0.190	0.5528
2.627	0.100	0.195	0.5701
2.700	0.100	0.200	0.5869
2.773	0.100	0.205	0.6032
2.846	0.100	0.210	0.6190
2.919	0.100	0.216	0.6343
2.992	0.100	0.221	0.6491
3.065	0.100	0.226	0.6634
3.138	0.100	0.231	0.6772
3.211	0.100	0.236	0.6905
3.284	0.100	0.241	0.7033
3.357	0.100	0.246	0.7157
3.430	0.100	0.251	0.7276
3.503	0.100	0.256	0.7391
3.576	0.100	0.262	0.7501
<u>>3.649</u>	0.100	0.267	1.0000

Mean catch = 0.1765

Variance = 0.00555

Standard deviation = 0.07448

% time no catch = 0.0%

Median population size = 2.335

% time population is ≤ 0.5 = 1.56%

% time population is ≤ 1.0 = 10.69%

Expected catch is roughly 0.074 x population

if population is greater than 0.073.

Table 1 (c).--Total economic return, effort restricted to be no greater than 0.1.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0000
0.146	0.000	0.000	0.0002
0.219	0.000	0.000	0.0011
0.292	0.000	0.000	0.0032
0.365	0.000	0.000	0.0071
0.438	0.000	0.000	0.0129
0.511	0.000	0.000	0.0207
0.584	0.000	0.000	0.0304
0.657	0.044	0.023	0.0419
0.730	0.100	0.056	0.0551
0.803	0.100	0.062	0.0698
0.876	0.100	0.067	0.0858
0.949	0.100	0.073	0.1030
1.022	0.100	0.078	0.1212
1.095	0.100	0.084	0.1403
1.168	0.100	0.089	0.1601
1.241	0.100	0.094	0.1806
1.314	0.100	0.100	0.2015
1.387	0.100	0.105	0.2228
1.460	0.100	0.111	0.2444
1.533	0.100	0.116	0.2661
1.606	0.100	0.122	0.2879
1.679	0.100	0.127	0.3097
1.752	0.100	0.132	0.3314
1.824	0.100	0.137	0.3530
1.897	0.100	0.143	0.3744
1.970	0.100	0.148	0.3955
2.043	0.100	0.153	0.4163
2.116	0.100	0.158	0.4368
2.189	0.100	0.164	0.4569

Table 1 (c).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.262	0.100	0.169	0.4766
2.335	0.100	0.174	0.4959
2.408	0.100	0.179	0.5147
2.481	0.100	0.185	0.5331
2.554	0.100	0.190	0.5510
2.627	0.100	0.195	0.5684
2.700	0.100	0.200	0.5853
2.773	0.100	0.205	0.6017
2.846	0.100	0.210	0.6176
2.919	0.100	0.216	0.6330
2.992	0.100	0.221	0.6479
3.065	0.100	0.226	0.6623
3.138	0.100	0.231	0.6762
3.211	0.100	0.236	0.6896
3.284	0.100	0.241	0.7025
3.357	0.100	0.246	0.7149
3.430	0.100	0.251	0.7269
3.503	0.100	0.256	0.7384
3.576	0.100	0.262	0.7495
>3.649	0.100	0.267	1.0000

Mean catch = 0.1756

Variance = 0.00586

Standard deviation = 0.07658

% time no catch = 3.04%

Median population size = 2.335

% time population is ≤ 0.5 = 1.29%

% time population is ≤ 1.0 = 10.30%

Table 1 (d).--Total discounted harvest and total economic return,
effort restricted to be no more than 0.1, no harvesting if population
size is less than 1 million tons.

Mean harvest = 0.1729

Variance = 0.00691

Standard deviation = 0.08310

% time no harvest = 9.59%

Median population size = 2.335

% time population is ≤ 0.5 = 1.05%

% time population is ≤ 1.0 = 9.59%

Table 1 (e).--Total discounted harvest, effort restricted to be
no greater than 0.2.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0000
0.146	0.000	0.000	0.0009
0.219	0.000	0.000	0.0042
0.292	0.000	0.000	0.0107
0.365	0.200	0.055	0.0204
0.438	0.200	0.065	0.0330
0.511	0.200	0.076	0.0480
0.584	0.200	0.087	0.0651
0.657	0.200	0.098	0.0840
0.730	0.200	0.108	0.1043
0.803	0.200	0.119	0.1258
0.876	0.200	0.129	0.1482
0.949	0.200	0.140	0.1713
1.022	0.200	0.150	0.1949
1.095	0.200	0.161	0.2189
1.168	0.200	0.171	0.2430
1.241	0.200	0.182	0.2672
0.314	0.200	0.192	0.2914
1.387	0.200	0.203	0.3154
1.460	0.200	0.213	0.3392
1.533	0.200	0.223	0.3627
1.606	0.200	0.234	0.3858
1.679	0.200	0.244	0.4085
1.752	0.200	0.254	0.4308
1.824	0.200	0.264	0.4526
1.897	0.200	0.274	0.4738
1.970	0.200	0.285	0.4945
2.043	0.200	0.295	0.5146
2.116	0.200	0.305	0.5342

Table 1 (e).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.189	0.200	0.315	0.5532
2.262	0.200	0.325	0.5716
2.335	0.200	0.335	0.5894
2.408	0.200	0.345	0.6066
2.481	0.200	0.355	0.6232
2.554	0.200	0.365	0.6392
2.627	0.200	0.375	0.6546
2.700	0.200	0.385	0.6695
2.773	0.200	0.395	0.6838
2.846	0.200	0.405	0.6976
2.919	0.200	0.415	0.7108
2.992	0.200	0.425	0.7235
3.065	0.200	0.435	0.7357
3.138	0.200	0.444	0.7474
3.211	0.200	0.454	0.7586
3.284	0.200	0.464	0.7693
3.357	0.200	0.474	0.7796
3.430	0.200	0.484	0.7895
3.503	0.200	0.494	0.7989
3.576	0.200	0.503	0.8079
>3.649	0.200	0.513	1.0000

Mean catch = 0.3055

Variance = 0.02217

Standard deviation = 0.14890

% time no catch = 1.07%

Median population size = 1.970

% time population is ≤ 0.5 = 3.3%

% time population is ≤ 1.0 = 17.13%

Table 1 (f).--Total discounted harvest, effort restricted to be no greater than 0.2, no harvest if population size is less than 1 million tons.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0000
0.146	0.000	0.000	0.0002
0.219	0.000	0.000	0.0014
0.292	0.000	0.000	0.0043
0.365	0.000	0.000	0.0095
0.438	0.000	0.000	0.0175
0.511	0.000	0.000	0.0283
0.584	0.000	0.000	0.0418
0.657	0.000	0.000	0.0577
0.730	0.000	0.000	0.0758
0.803	0.000	0.000	0.0957
0.876	0.000	0.000	0.1171
0.949	0.000	0.000	0.1396
1.022	0.200	0.150	0.1630
1.095	0.200	0.161	0.1871
1.168	0.200	0.171	0.2116
1.241	0.200	0.182	0.2363
1.314	0.200	0.192	0.2611
1.387	0.200	0.203	0.2859
1.460	0.200	0.213	0.3105
1.533	0.200	0.223	0.3349
1.606	0.200	0.234	0.3589
1.679	0.200	0.244	0.3825
1.752	0.200	0.254	0.4057
1.824	0.200	0.264	0.4284
1.897	0.200	0.274	0.4506
1.970	0.200	0.285	0.4722
2.043	0.200	0.295	0.4932

Table 1 (f).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.116	0.200	0.305	0.5136
2.189	0.200	0.315	0.5334
2.262	0.200	0.325	0.5526
2.335	0.200	0.335	0.5712
2.408	0.200	0.345	0.5891
2.481	0.200	0.355	0.6064
2.554	0.200	0.365	0.6231
2.627	0.200	0.375	0.6392
2.700	0.200	0.385	0.6547
2.773	0.200	0.395	0.6696
2.846	0.200	0.405	0.6840
2.919	0.200	0.415	0.6978
2.992	0.200	0.425	0.7111
3.065	0.200	0.434	0.7238
3.138	0.200	0.444	0.7360
3.211	0.200	0.454	0.7477
3.284	0.200	0.464	0.7589
3.357	0.200	0.474	0.7697
3.430	0.200	0.484	0.7800
3.503	0.200	0.494	0.7899
3.576	0.200	0.503	0.7993
<u>>3.649</u>	0.200	0.513	1.0000

Mean catch = 0.3008

Variance = 0.02812

Standard deviation = 0.16769

% time no harvest = 13.96%

Median population size = 2.043

% time population is ≤ 0.5 = 1.75%

% time population is ≤ 1.0 = 13.96%

Table 1 (g).--Total discounted economic value, effort restricted to be no greater than 0.2.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0000
0.146	0.000	0.000	0.0003
0.219	0.000	0.000	0.0016
0.292	0.000	0.000	0.0049
0.365	0.000	0.000	0.0108
0.438	0.000	0.000	0.0197
0.511	0.000	0.000	0.0315
0.584	0.000	0.000	0.0460
0.657	0.000	0.000	0.0629
0.730	0.000	0.000	0.0818
0.803	0.048	0.050	0.1024
0.876	0.124	0.082	0.1243
0.949	0.188	0.132	0.1472
1.022	0.200	0.150	0.1709
1.095	0.200	0.161	0.1951
1.168	0.200	0.171	0.2197
1.241	0.200	0.182	0.2444
1.314	0.200	0.192	0.2692
1.387	0.200	0.203	0.2939
1.460	0.200	0.213	0.3184
1.533	0.200	0.223	0.3426
1.606	0.200	0.234	0.3664
1.679	0.200	0.244	0.3898
1.752	0.200	0.254	0.4127
1.824	0.200	0.264	0.4351
1.897	0.200	0.274	0.4570
1.970	0.200	0.285	0.4783
2.043	0.200	0.295	0.4991
2.116	0.200	0.305	0.5193
2.189	0.200	0.315	0.5389

Table 1 (g).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.262	0.200	0.325	0.5579
2.335	0.200	0.335	0.5762
2.408	0.200	0.345	0.5939
2.481	0.200	0.355	0.6110
2.554	0.200	0.365	0.6275
2.627	0.200	0.375	0.6434
2.700	0.200	0.385	0.6587
2.773	0.200	0.395	0.6735
2.846	0.200	0.405	0.6877
2.919	0.200	0.415	0.7013
2.992	0.200	0.425	0.7144
3.065	0.200	0.435	0.7270
3.138	0.200	0.444	0.7391
3.211	0.200	0.454	0.7507
3.284	0.200	0.464	0.7618
3.357	0.200	0.474	0.7724
3.430	0.200	0.484	0.7826
3.503	0.200	0.494	0.7923
3.576	0.200	0.503	0.8016
>3.649	0.200	0.513	1.0000

Mean catch = 0.3031

Variance = 0.02593

Standard deviation = 0.16103

% time no catch = 8.18%

Median population size = 2.043

% time population is ≤ 0.5 = 1.97%

% time population is ≤ 1.0 = 14.72%

Table 1 (h).--Total discounted economic value, effort restricted to be greater than 0.2, no harvest if population is less than 1 million tons

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0000
0.146	0.000	0.000	0.0002
0.219	0.000	0.000	0.0014
0.292	0.000	0.000	0.0043
0.365	0.000	0.000	0.0095
0.438	0.000	0.000	0.0175
0.511	0.000	0.000	0.0283
0.584	0.000	0.000	0.0418
0.657	0.000	0.000	0.0577
0.730	0.000	0.000	0.0758
0.803	0.000	0.000	0.0957
0.876	0.000	0.000	0.1171
0.949	0.000	0.000	0.1396
1.022	0.200	0.150	0.1630
1.095	0.200	0.161	0.1871
1.168	0.200	0.171	0.2116
1.241	0.200	0.182	0.2363
1.314	0.200	0.192	0.2611
1.387	0.200	0.203	0.2859
1.460	0.200	0.213	0.3105
1.533	0.200	0.223	0.3349
1.606	0.200	0.234	0.3589
1.679	0.200	0.244	0.3825
1.752	0.200	0.254	0.4057
1.824	0.200	0.264	0.4284
1.897	0.200	0.274	0.4506
1.970	0.200	0.285	0.4722
2.043	0.200	0.295	0.4932

Table 1 (h).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.116	0.200	0.305	0.5136
2.189	0.200	0.315	0.5334
2.262	0.200	0.325	0.5526
2.335	0.200	0.335	0.5712
2.408	0.200	0.345	0.5891
2.481	0.200	0.355	0.6064
2.554	0.200	0.365	0.6231
2.627	0.200	0.375	0.6392
2.700	0.200	0.385	0.6547
2.773	0.200	0.395	0.6696
2.846	0.200	0.405	0.6840
2.919	0.200	0.415	0.6978
2.992	0.200	0.425	0.7111
3.065	0.200	0.435	0.7238
3.138	0.200	0.444	0.7360
3.211	0.200	0.454	0.7477
3.284	0.200	0.464	0.7589
3.357	0.200	0.474	0.7697
3.430	0.200	0.484	0.7800
3.503	0.200	0.494	0.7899
3.576	0.200	0.503	0.7993
>3.649	0.200	0.513	1.0000

Mean catch = 0.3008

Variance = 0.02812

Standard deviation = 0.16769

% time no catch = 13.96%

Median population size = 2.043

% time population is ≤ 0.5 = 1.75%

% time population is ≤ 1.0 = 13.96%

Table 1.(i).--Total discounted harvest, effort restricted to be no greater than 0.4.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0001
0.146	0.000	0.000	0.0017
0.219	0.000	0.000	0.0072
0.292	0.000	0.000	0.0183
0.365	0.000	0.000	0.0353
0.438	0.000	0.000	0.0576
0.511	0.000	0.000	0.0840
0.584	0.000	0.000	0.1134
0.657	0.056	0.029	0.1447
0.730	0.320	0.166	0.1771
0.803	0.400	0.221	0.2100
0.876	0.400	0.241	0.2428
0.949	0.400	0.260	0.2752
1.022	0.400	0.280	0.3070
1.095	0.400	0.299	0.3380
1.168	0.400	0.319	0.3680
1.241	0.400	0.338	0.3970
1.314	0.400	0.357	0.4250
1.387	0.400	0.377	0.4519
1.460	0.400	0.396	0.4778
1.533	0.400	0.415	0.5026
1.606	0.400	0.434	0.5264
1.679	0.400	0.453	0.5491
1.752	0.400	0.472	0.5708
1.824	0.400	0.491	0.5916
1.897	0.400	0.510	0.6114
1.970	0.400	0.528	0.6303
2.043	0.400	0.547	0.6484
2.116	0.400	0.567	0.6656

Table 1 (i).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.189	0.400	0.585	0.6820
2.262	0.400	0.604	0.6976
2.335	0.400	0.623	0.7125
2.408	0.400	0.641	0.7267
2.481	0.400	0.660	0.7402
2.554	0.400	0.678	0.7530
2.627	0.400	0.697	0.7652
2.700	0.400	0.715	0.7768
2.773	0.400	0.734	0.7878
2.846	0.400	0.752	0.7983
2.919	0.400	0.770	0.8083
2.992	0.400	0.789	0.8178
3.065	0.400	0.807	0.8268
3.138	0.400	0.825	0.8354
3.211	0.400	0.843	0.8435
3.284	0.400	0.861	0.8512
3.357	0.400	0.880	0.8585
3.430	0.400	0.898	0.8655
3.503	0.400	0.916	0.8721
3.576	0.400	0.934	0.8784
>3.649	0.400	0.952	1.0000

Mean catch = 0.4600

Variance = 0.08860

Standard deviation = 0.29766

% time no catch = 11.34%

Median population size = 1.533

% time population is ≤ 0.5 = 5.76%

% time population is ≤ 1.0 = 27.52%

Table 1 (j).--Total discounted harvest, effort restricted to be no greater than 0.4, no harvest allowed if population is less than 1 million tons.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0001
0.146	0.000	0.000	0.0013
0.219	0.000	0.000	0.0053
0.292	0.000	0.000	0.0134
0.365	0.000	0.000	0.0261
0.438	0.000	0.000	0.0434
0.511	0.000	0.000	0.0648
0.584	0.000	0.000	0.0897
0.657	0.000	0.000	0.1174
0.730	0.000	0.000	0.1471
0.803	0.000	0.000	0.1781
0.876	0.000	0.000	0.2099
0.949	0.000	0.000	0.2419
1.022	0.400	0.280	0.2738
1.095	0.400	0.300	0.3054
1.168	0.400	0.319	0.3363
1.241	0.400	0.338	0.3665
1.314	0.400	0.357	0.3958
1.387	0.400	0.377	0.4241
1.460	0.400	0.396	0.4514
1.533	0.400	0.415	0.4776
1.606	0.400	0.434	0.5028
1.679	0.400	0.453	0.5269
1.752	0.400	0.472	0.5500
1.824	0.400	0.491	0.5720
1.897	0.400	0.510	0.5930
1.970	0.400	0.529	0.6131
2.043	0.400	0.547	0.6322
2.116	0.400	0.567	0.6504

Table 1 (j).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.189	0.400	0.585	0.6678
2.262	0.400	0.604	0.6843
2.335	0.400	0.623	0.7000
2.408	0.400	0.641	0.7150
2.481	0.400	0.660	0.7292
2.554	0.400	0.678	0.7427
2.627	0.400	0.697	0.7555
2.700	0.400	0.715	0.7677
2.773	0.400	0.734	0.7793
2.846	0.400	0.752	0.7903
2.919	0.400	0.770	0.8008
2.992	0.400	0.789	0.8107
3.065	0.400	0.807	0.8201
3.138	0.400	0.825	0.8291
3.211	0.400	0.843	0.8376
3.284	0.400	0.861	0.8457
3.357	0.400	0.880	0.8534
3.430	0.400	0.898	0.8607
3.503	0.400	0.916	0.8676
3.576	0.400	0.934	0.8742
>3.649	0.400	0.952	1.0000

Mean catch = 0.4501

Variance = 0.10431

Standard deviation = 0.32297

% time no catch = 24.19%

Median population size = 1.606

% time population is ≤ 0.5 = 4.34%

% time population is ≤ 1.0 = 24.19%

Table 1 (k).--Total discounted economic value, effort restricted to be no greater than 0.4.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0001
0.146	0.000	0.000	0.0011
0.219	0.000	0.000	0.0046
0.292	0.000	0.000	0.0116
0.365	0.000	0.000	0.0227
0.438	0.000	0.000	0.0380
0.511	0.000	0.000	0.0572
0.584	0.000	0.000	0.0798
0.657	0.000	0.000	0.1051
0.730	0.000	0.000	0.1325
0.803	0.000	0.000	0.1614
0.876	0.056	0.038	0.1914
0.949	0.120	0.086	0.2218
1.022	0.176	0.134	0.2524
1.095	0.216	0.173	0.2828
1.168	0.256	0.215	0.3128
1.241	0.280	0.247	0.3423
1.314	0.304	0.281	0.3711
1.387	0.328	0.317	0.3991
1.460	0.344	0.347	0.4262
1.533	0.352	0.372	0.4524
1.606	0.360	0.396	0.4776
1.679	0.368	0.422	0.5019
1.752	0.376	0.448	0.5252
1.824	0.384	0.474	0.5476
1.897	0.384	0.492	0.5690
1.970	0.384	0.511	0.5895
2.043	0.392	0.538	0.6091
2.116	0.392	0.557	0.6278

Table 1 (k).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.189	0.392	0.575	0.6457
0.262	0.384	0.583	0.6628
2.335	0.384	0.601	0.6791
2.408	0.384	0.619	0.6946
2.481	0.384	0.637	0.7094
2.554	0.384	0.655	0.7235
2.627	0.376	0.661	0.7369
2.700	0.376	0.678	0.7497
2.773	0.368	0.683	0.7619
2.846	0.368	0.700	0.7735
2.919	0.368	0.717	0.7845
2.992	0.360	0.720	0.7950
3.065	0.360	0.737	0.8050
3.138	0.352	0.739	0.8145
3.211	0.352	0.755	0.8235
3.284	0.352	0.772	0.8321
3.357	0.344	0.772	0.8403
3.430	0.344	0.788	0.8481
3.503	0.336	0.788	0.8555
3.576	0.336	0.803	0.8625
>3.649	0.336	0.819	1.0000

Mean catch = 0.4184

Variance = 0.08364

Standard deviation = 0.28921

% time no catch = 16.14%

Median population size = 1.679

% time population is ≤ 0.5 = 3.8%

% time population is ≤ 1.0 = 22.18%

Table 1 (2).--Total discounted economic value, effort restricted to be no greater than 0.4, no harvest if population less than 1 million tons.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0001
0.146	0.000	0.000	0.0011
0.219	0.000	0.000	0.0045
0.292	0.000	0.000	0.0113
0.365	0.000	0.000	0.0221
0.438	0.000	0.000	0.0370
0.511	0.000	0.000	0.0557
0.584	0.000	0.000	0.0777
0.657	0.000	0.000	0.1025
0.730	0.000	0.000	0.1295
0.803	0.000	0.000	0.1581
0.876	0.000	0.000	0.1877
0.949	0.000	0.000	0.2179
1.022	0.176	0.134	0.2484
1.095	0.216	0.172	0.2788
1.168	0.256	0.215	0.3088
1.241	0.280	0.247	0.3383
1.314	0.304	0.281	0.3671
1.387	0.328	0.317	0.3952
1.460	0.344	0.347	0.4224
1.533	0.352	0.372	0.4487
1.606	0.360	0.396	0.4741
1.679	0.368	0.422	0.4985
1.752	0.376	0.448	0.5220
1.824	0.384	0.474	0.5445
1.897	0.384	0.492	0.5661
1.970	0.384	0.511	0.5868
2.043	0.392	0.538	0.6066
2.116	0.392	0.557	0.6255

Table 1 (2).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.189	0.392	0.575	0.6435
2.262	0.384	0.583	0.6607
2.335	0.384	0.601	0.6771
2.408	0.384	0.619	0.6927
2.481	0.384	0.637	0.7076
2.554	0.376	0.655	0.7218
2.627	0.376	0.661	0.7353
2.700	0.376	0.678	0.7482
2.773	0.368	0.683	0.7605
2.846	0.368	0.700	0.7722
2.919	0.368	0.717	0.7833
2.992	0.360	0.720	0.7939
3.065	0.360	0.737	0.8040
3.138	0.352	0.739	0.8136
3.211	0.352	0.755	0.8227
3.284	0.352	0.772	0.8314
3.357	0.344	0.772	0.8396
3.430	0.344	0.788	0.8474
3.503	0.336	0.788	0.8548
3.576	0.336	0.803	0.8619
>3.649	0.336	0.819	1.0000

Mean catch = 0.4168

Variance = 0.08600

Standard deviation = 0.29322

% time no catch = 21.79%

Median population size = 1.679

% time population is ≤ 0.5 = 3.7%

% time population is ≤ 1.0 = 21.79%

Table 1 (m).--Total discounted harvest, effort restricted to be no greater than 0.6.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0003
0.146	0.000	0.000	0.0023
0.219	0.000	0.000	0.0083
0.292	0.000	0.000	0.0202
0.365	0.000	0.000	0.0385
0.438	0.000	0.000	0.0630
0.511	0.000	0.000	0.0927
0.584	0.000	0.000	0.1265
0.657	0.000	0.000	0.1631
0.730	0.000	0.000	0.2013
0.803	0.000	0.000	0.2403
0.876	0.072	0.049	0.2792
0.949	0.264	0.180	0.3175
1.022	0.444	0.306	0.3548
1.095	0.600	0.419	0.3908
1.168	0.600	0.446	0.4253
1.241	0.600	0.473	0.4582
1.314	0.600	0.500	0.4895
1.387	0.600	0.527	0.5191
1.460	0.600	0.554	0.5471
1.533	0.600	0.581	0.5735
1.606	0.600	0.607	0.5984
1.679	0.600	0.634	0.6218
1.752	0.600	0.660	0.6438
1.824	0.600	0.687	0.6645
1.897	0.600	0.713	0.6839
1.970	0.600	0.740	0.7022
2.043	0.600	0.766	0.7194
2.116	0.600	0.792	0.7355

Table 1 (m).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.189	0.600	0.818	0.7506
2.262	0.600	0.844	0.7648
2.335	0.600	0.870	0.7782
2.408	0.600	0.896	0.7908
2.481	0.600	0.922	0.8026
2.554	0.600	0.948	0.8137
2.627	0.600	0.974	0.8242
2.700	0.600	0.999	0.8340
2.773	0.600	1.025	0.8433
2.846	0.600	1.050	0.8520
2.919	0.600	1.076	0.8602
2.992	0.600	1.102	0.8679
3.065	0.600	1.127	0.8752
3.138	0.600	1.152	0.8820
3.211	0.600	1.178	0.8884
3.284	0.600	1.203	0.8945
3.357	0.600	1.228	0.9002
3.430	0.600	1.253	0.9056
3.503	0.600	1.279	0.9107
3.576	0.600	1.304	0.9155
>3.649	0.600	1.329	1.0000

Mean catch = 0.5348

Variance = 0.18809

Standard deviation = 0.43369

% time no catch = 24.03%

Median population size = 1.387

% time population is ≤ 0.5 = 6.3%

% time population is ≤ 1.0 = 31.75%

For $x \geq 1.095$, expected catch is roughly $0.356x + 0.029$

Table 1 (n) .--Total discounted harvest, effort restricted to be no greater than 0.6, no harvesting allowed if population is less than 1 million tons.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0003
0.146	0.000	0.000	0.0022
0.219	0.000	0.000	0.0080
0.292	0.000	0.000	0.0194
0.365	0.000	0.000	0.0369
0.438	0.000	0.000	0.0603
0.511	0.000	0.000	0.0888
0.584	0.000	0.000	0.1214
0.657	0.000	0.000	0.1569
0.730	0.000	0.000	0.1942
0.803	0.000	0.000	0.2324
0.876	0.000	0.000	0.2708
0.949	0.000	0.000	0.3088
1.022	0.444	0.306	0.3459
1.095	0.600	0.419	0.3819
1.168	0.600	0.446	0.4165
1.241	0.600	0.473	0.4496
1.314	0.600	0.500	0.4811
1.387	0.600	0.527	0.5110
1.460	0.600	0.554	0.5393
1.533	0.600	0.581	0.5660
1.606	0.600	0.607	0.5912
1.679	0.600	0.634	0.6150
1.752	0.600	0.660	0.6374
1.824	0.600	0.687	0.6584
1.897	0.600	0.713	0.6782
1.970	0.600	0.740	0.6968
2.043	0.600	0.766	0.7143
2.116	0.600	0.792	0.7307

Table 1 (n).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.189	0.600	0.818	0.7461
2.262	0.600	0.844	0.7606
2.335	0.600	0.870	0.7742
2.408	0.600	0.896	0.7870
2.481	0.600	0.922	0.7990
2.554	0.600	0.948	0.8103
2.627	0.600	0.974	0.8209
2.700	0.600	0.999	0.8309
2.773	0.600	1.025	0.8403
2.846	0.600	1.050	0.8492
2.919	0.600	1.076	0.8575
2.992	0.600	1.102	0.8654
3.065	0.600	1.127	0.8728
3.138	0.600	1.152	0.8798
3.211	0.600	1.178	0.8864
3.284	0.600	1.203	0.8926
3.357	0.600	1.228	0.8984
3.430	0.600	1.253	0.9039
3.503	0.600	1.279	0.9091
3.576	0.600	1.304	0.9140
>3.649	0.600	1.329	1.0000

Mean catch = 0.5337

Variance = 0.19546

Standard deviation = 0.442113

% time no catch = 30.88%

Median population size = 1.387

% time population is $\leq$ 0.5 = 6.03%

% time population is $\leq$ 1.0 = 30.88%

Table 1 (o).--Total discounted economic return, effort restricted
to be no greater than 0.6.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0001
0.146	0.000	0.000	0.0011
0.219	0.000	0.000	0.0046
0.292	0.000	0.000	0.0116
0.365	0.000	0.000	0.0227
0.438	0.000	0.000	0.0380
0.511	0.000	0.000	0.0572
0.584	0.000	0.000	0.0797
0.657	0.000	0.000	0.1050
0.730	0.000	0.000	0.1324
0.803	0.000	0.000	0.1613
0.876	0.060	0.041	0.1912
0.949	0.120	0.086	0.2216
1.022	0.168	0.128	0.2521
1.095	0.216	0.173	0.2825
1.168	0.252	0.212	0.3125
1.241	0.288	0.253	0.3419
1.314	0.312	0.288	0.3706
1.387	0.324	0.314	0.3985
1.460	0.336	0.340	0.4256
1.533	0.360	0.368	0.4518
1.606	0.360	0.396	0.4770
1.679	0.372	0.426	0.5013
1.752	0.372	0.444	0.5246
1.824	0.384	0.474	0.5270
1.897	0.384	0.492	0.5484
1.970	0.384	0.511	0.5689
2.043	0.384	0.529	0.5885
2.116	0.384	0.547	0.6072

Table 1 (o).--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.189	0.384	0.565	0.6251
2.262	0.384	0.583	0.6422
2.335	0.384	0.601	0.6585
2.408	0.384	0.619	0.6740
2.481	0.384	0.637	0.6888
2.554	0.384	0.655	0.7029
2.627	0.372	0.655	0.7164
2.700	0.372	0.672	0.7292
2.773	0.372	0.689	0.7414
2.846	0.372	0.706	0.7530
2.919	0.360	0.703	0.7641
2.992	0.360	0.720	0.7746
3.065	0.360	0.737	0.7846
3.138	0.360	0.754	0.7941
3.211	0.348	0.748	0.8032
3.284	0.348	0.764	0.8118
3.357	0.348	0.780	0.8200
3.430	0.348	0.796	0.8278
3.503	0.336	0.788	0.8352
3.576	0.336	0.803	0.8422
>3.649	0.336	0.819	1.0000

Mean catch = 0.4181

Variance = 0.08349

Standard deviation = 0.28895

% time no catch = 16.13%

Median population size = 1.679

% time population is ≤ 0.5 = 3.8%

% time population is ≤ 1.0 = 22.16%

Table 1 (p).--Total discounted economic value, effort restricted to be no greater than 0.6, no harvesting if population is less than 1 million tons.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
0.073	0.000	0.000	0.0001
0.146	0.000	0.000	0.0011
0.219	0.000	0.000	0.0045
0.292	0.000	0.000	0.0113
0.365	0.000	0.000	0.0221
0.438	0.000	0.000	0.0369
0.511	0.000	0.000	0.0555
0.584	0.000	0.000	0.0775
0.657	0.000	0.000	0.1023
0.730	0.000	0.000	0.1292
0.803	0.000	0.000	0.1577
0.876	0.000	0.000	0.1863
0.949	0.000	0.000	0.2165
1.022	0.168	0.128	0.2469
1.095	0.216	0.173	0.2772
1.168	0.252	0.212	0.3072
1.241	0.288	0.253	0.3367
1.314	0.312	0.288	0.3655
1.387	0.324	0.314	0.3936
1.460	0.336	0.340	0.4208
1.533	0.348	0.368	0.4471
1.606	0.360	0.396	0.4725
1.679	0.372	0.426	0.4969
1.752	0.372	0.444	0.5204
1.824	0.384	0.474	0.5429
1.897	0.384	0.492	0.5645
1.970	0.384	0.511	0.5852
2.043	0.384	0.529	0.6050
2.116	0.384	0.547	0.6239

Table 1 (p) .--Continued.

State (tons x 10 ⁶)	Optimal effort	Expected catch	Stationary distribution
2.189	0.384	0.565	0.6419
2.262	0.384	0.583	0.6591
2.335	0.384	0.601	0.6755
2.408	0.384	0.619	0.6912
2.481	0.384	0.637	0.7061
2.554	0.384	0.655	0.7203
2.627	0.372	0.655	0.7338
2.700	0.372	0.672	0.7467
2.773	0.372	0.689	0.7590
2.846	0.372	0.706	0.7707
2.919	0.360	0.703	0.7818
2.992	0.360	0.720	0.7924
3.065	0.360	0.737	0.8025
3.138	0.360	0.754	0.8121
3.211	0.348	0.748	0.8212
3.284	0.348	0.764	0.8299
3.357	0.348	0.780	0.8381
3.430	0.348	0.796	0.8459
3.503	0.336	0.788	0.8533
3.576	0.336	0.803	0.8604
>3.649	0.336	0.819	1.0000

Mean catch = 0.4164

Variance = 0.08601

Standard deviation = 0.29328

% time no catch = 21.65%

Median population size = 1.679

% time population is ≤ 0.5 = 3.69%

% time population is ≤ 1.0 = 21.65%

Table 2.--Statistics for present anchovy management alternatives
(from Pacific Fishery Management Council 1978).

	Policy					
	1	2	3	4	5	6
% time population is ≤ 0.5	3.4%	4.4%	5.1%	3.0%	8.5%	9.6%
% time population is ≤ 1.0	16.1%	20.0%	20.8%	14.1%	30.3%	32.3%
% time no fishery	16.1%	20.0%	5.1%	14.1%	30.3%	9.6%

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FISHERIES AND FISHERY DEVELOPMENT POTENTIAL OF THE
GILBERT ISLANDS COLONY INCLUDING FANNING AND
CHRISTMAS ISLANDS

Richard N. Uchida¹

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¹Southwest Fisheries Center, National Marine Fisheries Service,
NOAA, Honolulu, HI 96812.

GILBERT ISLANDS

Fishing is primarily a subsistence activity in the 16 islands comprising the Gilbert Islands located near the equator between lat. 4°N and 3°S and long. 172° and 177°E. Nearly every family owns an outrigger canoe and most of the islanders are proficient canoe handlers and fishermen. Also popular are outboard motor powered 3.6-m fiber glass boats which in recent years have contributed to an increase in catch.

On the reef flats, the method of fishing either during day or night, varies widely from hand gathering of shellfish, octopus, spiny lobsters, crabs, and small fish, to trapping with large stone traps. Other gear commonly used for reef fishing are pole and line, dip net, and spear. Inside the lagoons, where about 80% of the fishing effort is expended, the primary gear used is the monofilament gill net. Other gear used in the lagoons are spears and handlines. Lagoon catches are dominated by parrotfish, Scaridae, mullet, Mugil vaigiensis, bonefish, Albula vulpes, mountain bass, Kuhlia sandvicensis, milkfish, Chanos chanos, jacks, Carangidae, groupers, Serranidae, and snappers, Lutjanidae. Occasionally, the sardines, Herklotsichthys punctatus, which enter the lagoon are captured with a cast net.

No commercial fishery for tuna exists in the Gilberts. According to resident fishermen, however, skipjack tuna, Katsuwonus pelamis, and yellowfin tuna, Thunnus albacares, are caught throughout the year, principally by trolling in coastal waters from canoes and small

motorized boats. Also used are the traditional pole-and-line method with mother-of-pearl lures and deep handline. In addition to skip-jack and yellowfin tunas, other troll-caught species include billfishes, Istiophoridae, jacks, wahoo, Acanthocybium solandri, rainbow runner, Elegatis bipinnulatus, and barracuda, Sphyraenidae; deep handline catches include sea bass, Serranidae, castor-oil fish, Ruvettus pretiosus, and sharks, Carcharhinidae. Dip net fishing in coastal waters is practiced at night to capture flyingfish.

Fish catches are usually divided first among relatives and friends of the fishermen and the surplus is sold directly to other consumers. The few fishermen who engage in commercial fishing usually sell their catches to the retail markets.

Culture of milkfish has been practiced for many years by either private groups or individuals in several of the islands in the Gilberts; however, these operations are now carried on only on a subsistence level, using traditional methods. Since the introduction of the cichlid fish tilapia, Tilapia mossambica, into the milkfish ponds several years ago, the culture of milkfish has been severely affected by slower growth and production has been drastically curtailed. Consequently the pond owners are now anxious to clear the ponds of tilapia. Government authorities have recognized that substantial improvements can be made in aquaculture among the various islands, particularly with respect to culture of milkfish.

A number of studies conducted in South Pacific islands indicate that the local fisheries supply adequate or abundant protein, but demographic changes have occurred in that the people are now in more crowded and non-traditional groups; therefore, there is now a problem of the distribution of protein. In the Gilberts, for example, there is clearly a mixed situation wherein Tarawa is usually short of fish and Onotoa to the south, where the population density is lower, has more than enough fish.

In general, there is no basis to estimate the potential size of the coastal benthic or nearshore pelagic resources with any degree of accuracy. Until 1970, no statistics were available for either fish landings or fishing effort from the Gilberts. According to FAO statistics, the estimated nominal catches of fish, crustaceans, and mollusks in the Gilberts rose from 200 metric tons (MT) in 1970 to 500 MT in 1971, remained at that level through 1973, then rose to 750 MT in 1974-76. Dominating the marine catch in the Gilberts are skipjack tuna (27%), percoid fishes such as sea basses and sea breams (19%), and clupeids such as sardines and other herringlike fishes (14%). Other important species are milkfish, goatfish, Mullidae, mojarras, Gerres spp., and mullet.

Concerning fishery development, there is considerable interest in developing a skipjack tuna pole-and-line fishery in the Gilberts. Although an inventory of the baitfish resource is not available at this time, past studies indicate that the sardine, H. punctatus, is sufficiently abundant in certain years, particularly in Tarawa lagoon

and Butaritari lagoon for use as live bait in pole-and-line fishing for skipjack tuna. However, obtaining sufficient quantities of live bait for sustained fishing is a major constraint in the development of a skipjack tuna fishery. In an attempt to resolve the problem of insufficient live bait, a UNDP/FAO project has been initiated to look into culturing juvenile milkfish as bait. The lagoon in Tarawa has been modified by the construction of a number of earthen ponds in which milkfish fry captured from wild stocks are placed. How the bait culture experiments are progressing is not known at the present time.

Although surface schooling skipjack and yellowfin tunas have potential for development of a pole-and-line fishery in the Gilberts, it is the large, deep-swimming tunas that have the greater potential. In the pelagic, non-coastal areas, deep-swimming tunas are taken by Japanese, Korean, and Taiwanese longline fishing vessels. Much of the exploratory research leading to the development of the fishery for the deep-swimming tunas in the central equatorial Pacific was conducted by the Pacific Oceanic Fishery Investigations, a predecessor agency of the Honolulu Laboratory, Southwest Fisheries Center, National Marine Fisheries Service.

The three most important species taken by longline are the yellowfin tuna, bigeye tuna, Thunnus obesus, albacore, T. alalunga. In 1975, Japanese, Korean, and Taiwanese longliners caught 12,091 MT of tunas and billfishes in the 200-mile conservation zone of the Gilbert Islands colony; albacore, yellowfin, and bigeye tunas

represented roughly 95% of the catch. The 1976 catches of these species by foreign longliners represented 94% of the 11,348 MT of tunas and billfishes landed. Other species usually taken by longliners are the northern bluefin tuna, Thunnus thynnus, southern bluefin tuna, T. maccoyii, skipjack tuna, swordfish, Xiphias gladius, blue marlin, Makaira nigricans, striped marlin, Tetrapturus audax, black marlin, Makaira indica, sailfish, Istiophorus platypterus, and shortbill spearfish, Tetrapturus angustirostris.

Ciguatera fish poisoning is a relatively serious problem in the Gilberts. A survey conducted in 1964 showed that ciguatoxic fishes occurred around 10 of the 16 islands and that toxic fishes were generally concentrated in open sea reefs and anchorages on the leeward side of the islands. Fish considered to be fatty are greatly appreciated by the Gilbertese; however, a number of these popular fatty fishes are known to be ciguatoxic. The Gilbertese recognize that some species of fatty fish may be toxic; however, they apparently find it impossible to resist eating them and frequent cases of fish poisoning are encountered in the Gilberts. Furthermore, those afflicted only mildly seldom report the attacks to the medical officer. Among the species most frequently implicated in ciguatera attacks were Epinephelus fuscoguttatus, Cephalopholis miniatus, Promicrops lanceolatus, Lutjanus bohar, Sphyaena sp., and Muraenidae. Interviews with Gilbertese have also disclosed that ciguateric symptoms occur after consuming the liver of some sharks, the heads of some mullets and goatfishes, the castor-oil fish, and some sardines.

In addition, the hawksbill turtle has been reported to be toxic. Among invertebrates two species of crab, Zoymus aeneus and Carpilius convexus, and one species of gastropod, Charonia tritonis, have been reported to be toxic.

FANNING AND CHRISTMAS ISLANDS

Fanning Island, which has been described as a beautiful atoll, is located at lat. 3°55'N, long. 159°23'W, and is part of the Gilbert Islands colony, which also includes Washington Island, Ocean Island, and those islands claimed by the United States, Caroline, Christmas, Flint, Malden, Starbuck, and Vostok in the Line Islands; and Birnie, Gardner, Hull, McKean, Phoenix, and Sydney in the Phoenix group. Fanning Island is composed of three islets, has a circumference of about 51 km (32 mi) and a land area of about 32.5 sq km (12.5 sq mi).

A cable station established in 1902 to serve as a connecting link of the Pacific cable between British Columbia and Suva, Fiji Islands, was abandoned in 1963. In 1966, the University of Hawaii, Honolulu, Hawaii, acquired a lease for the abandoned cable station from the former Gilbert and Ellice Islands Colony. A 760-m (2,500-ft) airstrip has since been added to the island by the University.

The land is owned by Fanning Island Plantation, Ltd., a subsidiary of Burns, Philp and Company, Ltd., Sydney, Australia. About 12.5 sq km (3,100 acres) of the total land area are under cultivation for copra production. It is presently inhabited by 600 Gilbertese copra workers.

Christmas Island, situated 284 km (153 nmi) southeast of Fanning Island at lat. 1°55'N, long. 157°20'W, is the largest coral atoll in the world, covering 640 sq km (247 sq mi) of which 321 sq km (124 sq mi) is land. The island is shaped like a lobster claw whose jaws open to the northwest. Within the claw is a shallow, semicircular 160 sq km (62 sq mi) lagoon dotted with numerous coral heads.

The island was discovered in 1777 and was included in the former colony of the Gilbert and Ellice Islands in 1919. British control of the island was disputed by the United States in 1936-38. Christmas Island is presently administered by the Gilbert Islands colony, but the United States has not relinquished its claim on the island.

There are two old settlements on the island--London and Paris--but the latter is deserted and in ruins. A third settlement, Poland, has been permanently occupied since June 1966.

In addition to the lagoon, Christmas Island has about 500 lakes with salinities varying widely from 35‰ to 330‰. At present, the Christmas Island plantation, which is owned and operated by the government, has 20 sq km (5,000 acres) under cultivation for copra production. The island has an excellent network of paved main roads and hardpan secondary roads. A 1,800-m (6,000-ft) runway is at the northern end of the island.

There are no established fisheries at Fanning or Christmas Islands; however, research cruises conducted during the 1950's by the Pacific Oceanic Fishery Investigations indicated the presence of numerous schools of skipjack and yellowfin tunas in the vicinity of Fanning

and Christmas Islands. In general, the data showed a peak in abundance of tuna schools in June-August and that yellowfin tuna schools were usually closer to the islands whereas skipjack tuna schools predominated in the semioceanic zone between 111 and 334 km (60 and 180 nmi) from land.

Although only a limited number of observations has been made on bait availability and abundance, it is quite apparent that bait is not abundant or in constant supply anywhere in the Line Islands. Among the species present in the Fanning lagoon suitable as bait for pole-and-line fishing are mountain bass and mullet, Mugil sp. At Christmas Island, bait scouting expeditions have revealed the presence of relatively large concentrations of goatfish and mullet (Mugilidae), but no fish of the silverside, anchovy, or herring families. One commercial vessel reportedly caught 200 scoops of juvenile mullet suitable as live bait for pole-and-line fishing. Because of the size of its lagoon, Christmas Island is potentially the most important baitfish source in the entire Line Island chain.

Several exploratory commercial and semi-commercial fishing trips have been made to the Line Islands to determine the potential for tuna pole-and-line fishing. In late 1947, the FV Pioneer caught 6.4 MT of yellowfin tuna mostly around Fanning and Christmas Islands. This trip was followed by another in 1949 when the FV Calistar, carrying 1,800 scoops of anchoveta, Cetengraulis mysticetus, caught at Magdalena Bay in Lower California, caught about 45 MT of yellowfin tuna near Fanning Island. In 1953, a Hawaiian sampan FV Tradewind

caught 5.9 MT of yellowfin tuna with 385 kg of baitfish, mostly small mullet and milkfish while fishing around Fanning Island. At Christmas Island, however, the bait supply was poor although skipjack tuna schools were quite numerous close to the island. In general, the major obstacle to successful pole-and-line fishing in the Line Islands is the absence of a constant and ample supply of live bait.

Purse seine fishing has also been attempted in the Line Islands area during the 1950's, but the conclusion drawn from these trials was that this fishing method was unsuitable because the tuna schools were too wild and they were usually too close to the islands' reef. The deep thermocline in this area also allowed the tuna schools to sound beneath the net.

Trolling offers another alternative for capturing tunas in the Line Islands; however, the catch rates during the surveys in the 1950's were not as high at Fanning and Christmas Islands as at other islands and atolls such as Kingman Reef, Palmyra, and Washington Islands. Skipjack and yellowfin tunas are the principal species caught by trolling in the Line Islands but other species that are likely to be caught include barracuda, Sphyraena barracuda, mahimahi, Coryphaena hippurus, wahoo, rainbow runner, and jacks.

Concerning fishery development for Christmas Island, it is believed that the potentials are good for brine shrimp culture and the development of sport, lobster, and tuna fisheries. Of these four projects, the most likely candidate for rapid development is sport fishing. A lobster fishery could also be developed rapidly because

little is required in terms of infrastructure. The size of the lobster population, however, is presently not known, but it is estimated to be rather large. Brine shrimp culture in the saline lakes of Christmas Island is technically and economically feasible. Commercial tuna fishing has the largest dollar potential to the Gilbertese, but development may be several years away due to the relatively high capital investment required for boats and other support facilities. Also, the potentials for the development of a fishery for the deep-swimming tunas that are presently being exploited by Japanese, Taiwanese, and Korean fishermen were discussed in the section on the Gilbert Islands.

Sport fishing at Christmas Island could include not only offshore trolling for tunas and tunalike fishes but also spin fishing, bottom handlining, and spear fishing for a wide variety of reef and bottom fishes including snappers, groupers, and carangids. There is, however, the ever-present danger that some species may be ciguatoxic. Research conducted by University of Hawaii scientists gave clear evidence that some species of red and gray snapper, a grouper, and a parrotfish are toxic at Fanning and Christmas Islands.

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COMPUTING STOCK SIZE INDICES FROM
CATCH-PER-UNIT-EFFORT STATISTICS

Jerry A. Wetherall
Southwest Fisheries Center
National Marine Fisheries Service, NOAA
Honolulu, Hawaii 96812

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Purpose

This note summarizes some of the fundamental relationships and equations for computing annual stock size indices using catch-per-unit-effort (CPUE) statistics, and gives simple expressions for estimating the sampling variance of such indices. It is motivated by the general need for some measure of precision to accompany the usual point estimates of relative population size, and by the specific desirability of using statistical weights when analyzing the stock indices by least squares methods.

Following the definition of terms and the statement of basic relations and estimators, two application situations are discussed. In Case 1, the spatial and temporal coverage of the fishery in the stock region is complete each year; in Case 2, coverage is not complete each year because of expansion or contraction of the fleet's range of operations or because of the seasonal absence of fishing activity in certain zones.

Notation

N_i	= Average stock size in year i in the defined stock region
N_{ijk}	= Average stock size in year i in the j^{th} fishing zone and k^{th} fishing season
n_i	= Number of potential fishing zones in the stock region in year i
r_i	= Number of potential fishing seasons during the i^{th} year
ℓ_i	= Actual number of seasons in which fishing took place in year i

- m_{ik} = Actual number of fishing zones in which effort was exerted during the k^{th} fishing season of year i
- p_{ijk} = Ratio of average stock size in the j^{th} fishing zone during the k^{th} season of year i to the average overall stock size during year i
- $\hat{N}_{i(jk)}$ = Estimate of N_i based on observations from the j^{th} fishing zone during the k^{th} fishing season of year i
- $\hat{u}_{i(jk)}$ = Stock size index corresponding to $\hat{N}_{i(jk)}$
- $\hat{u}_i$ = Overall index of stock size in year i
- $\hat{\sigma}_{\hat{u}_i}^2$ = Estimate of the variance of the overall index of stock size in year i
- $\hat{\sigma}_{\hat{u}_{i(jk)}}^2$ = Estimated variance among the individual indices of stock size in year i
- A_{ijk} = Area of the j^{th} fishing zone in which fishing occurred during the k^{th} season of year i
- C_{ijk} = Catch taken in the j^{th} fishing zone during the k^{th} season of year i
- f_{ijk} = Nominal fishing effort exerted in the j^{th} fishing zone during the k^{th} season of year i [adjusted for differences in fishing power, if any]
- q = Catchability coefficient (assumed constant)
- F_{ijk} = Instantaneous fishing mortality rate in fishing zone j during the k^{th} season of year i
- D_{ijk} = Average density of fish in the j^{th} fishing zone during the k^{th} fishing season of year i

- $CV(\hat{u}_i)$ = Coefficient of variation of the overall stock size index
in year i
- $\hat{f}_i$ = Effective fishing intensity during year i
- I_i = Concentration coefficient during year i
- a_{jk} = Number of "standard" years when fishing effort was
exerted in the " j^{th} " fishing zone during the " k^{th} "
fishing season
- $\hat{p}_{ijk}$ = Estimate of p_{ijk} based on statistics from the j^{th} fishing
zone during the k^{th} season of year i
- $\hat{p}_{jk}$ = Estimate of p_{ijk} based on an average of annual estimates
derived from "standard" years when fishing covered the
entire stock range and all fishing seasons

Basic Relations

We assume that the entire stock in question [or a constant fraction of some larger stock] occupies a defined stock region consisting in year i of n_i potential fishing zones and that there are r_i potential fishing seasons of equal duration. In the course of a particular year, fishing actually takes place during ℓ_i seasons ($\ell_i \leq r_i$), with m_{ik} ($m_{ik} \leq n_i$) fishing zones being occupied in the k^{th} season.

Following the standard deterministic theory of fishing, the catch in a particular season-zone stratum and year is described as the product of fishing mortality rate and stock density in the given stratum, i.e.,

$$C_{ijk} = F_{ijk} D_{ijk} = q f_{ijk} \left(\frac{N_{ijk}}{A_{ijk}} \right) \quad \dots (1)$$

We define

$$p_{ijk} = \frac{N_{ijk}}{\sum_{k=1}^{r_i} \left(\sum_{j=1}^{n_i} N_{ijk} \right) / r_i}$$

$$= \frac{N_{ijk}}{N_i}$$

$$\text{so that } N_{ijk} = p_{ijk} N_i \quad \dots (2)$$

Substituting (2) in (1) we obtain

$$C_{ijk} = \frac{q f_{ijk} p_{ijk} N_i}{A_{ijk}} \quad \dots (3)$$

Now regarding catch as an observed random variable, there is an estimate of the absolute stock size, N_i , arising from each time period and geographical stratum actually fished in year i , viz.,

$$\hat{N}_{i(jk)} = \left(\frac{1}{q} \right) \left(\frac{C_{ijk} A_{ijk}}{f_{ijk} p_{ijk}} \right)$$

We drop the constant catchability coefficient, q , to obtain a corresponding index of stock size based on observations in the $(jk)^{\text{th}}$ stratum,

$$\hat{u}_{i(jk)} = \frac{C_{ijk} A_{ijk}}{f_{ijk} p_{ijk}} .$$

The overall annual index of stock size is then computed as the average of the individual stratum estimates,

$$\begin{aligned}\hat{u}_i &= \frac{\sum_{k=1}^{\ell_i} \sum_{j=1}^{m_{ik}} \hat{u}_{i(jk)}}{\sum_{k=1}^{\ell_i} m_{ik}} \\ &= \frac{\sum_{k=1}^{\ell_i} \sum_{j=1}^{m_{ik}} \frac{C_{ijk} A_{ijk}}{f_{ijk} p_{ijk}}}{\sum_{k=1}^{\ell_i} m_{ik}} \quad \dots (4)\end{aligned}$$

Note that all elements of (4) are observed except for p_{ijk} , which must be estimated (see below).

The sampling variance of the stock size index is estimated by

$$\hat{\sigma}_{\hat{u}_i}^2 = \hat{\sigma}_{\hat{u}_{i(jk)}}^2 \Big/ \sum_{k=1}^{\ell_i} m_{ik} \quad \dots (5)$$

where

$$\hat{\sigma}_{\hat{u}_{i(jk)}}^2 = \frac{\sum_{k=1}^{\ell_i} \sum_{j=1}^{m_{ik}} \left(\hat{u}_{i(jk)} - \hat{u}_i \right)^2}{\left(\sum_{k=1}^{\ell_i} m_{ik} - 1 \right)}$$

and the coefficient of variation of $\hat{u}_i$ is

$$CV(\hat{u}_i) = \hat{\sigma}_{\hat{u}_i} / \hat{u}_i \quad .$$

An alternate way to compute the stock size index is as

$$\hat{u}_i = \frac{\sum_{k=1}^{\ell_i} \sum_{j=1}^{m_{ik}} C_{ijk}}{\sum_{k=1}^{\ell_i} \sum_{j=1}^{m_{ik}} \frac{f_{ijk} p_{ijk}}{A_{ijk}}}$$

$$= \frac{C_{i..}}{f'_i}$$

$$= \frac{C_{i..}}{I_i \sum_{k=1}^{\ell_i} \sum_{j=1}^{m_{ik}} \frac{f_{ijk}}{A_{ijk}}} / n_i$$

where f'_i is the effective fishing intensity in the i^{th} year and I_i is the corresponding concentration coefficient.

Note that I_i is here defined as

$$I_i = \frac{n_i \sum_{k=1}^{\ell_i} \sum_{j=1}^{m_{ik}} \frac{f_{ijk}}{A_{ijk}} p_{ijk}}{\sum_{k=1}^{\ell_i} \sum_{j=1}^{m_{ik}} \frac{f_{ijk}}{A_{ijk}}} .$$

Estimating p_{ijk}

The index described by (4) and its variance estimate given by (5) apply to all situations regardless of how completely the fishing fleet covers the stock region. However, the calculation of the p_{ijk} will differ depending on whether coverage is complete or not.

Case 1: Complete Coverage

When $\ell_i = r_i$ and $m_{ik} = n_i$ for all i and k , then it is possible to estimate the p_{ijk} 's individually as

$$\hat{p}_{ijk} = \frac{\left(\frac{C_{ijk} A_{ijk}}{f_{ijk}} \right)}{\sum_{k=1}^{\ell_i} \left(\sum_{j=1}^{m_{ik}} \frac{C_{ijk} A_{ijk}}{f_{ijk}} \right) / \ell_i} \quad \dots (8)$$

and in this event the stock size index reduces to

$$\hat{u}_i = \sum_{k=1}^{\ell_i} \left(\sum_{j=1}^{m_{ik}} \frac{C_{ijk} A_{ijk}}{f_{ijk}} \right) / \ell_i$$

Case 2: Incomplete Coverage

When $\ell_i < r_i$ and/or $m_{ik} < n_i$ for some i , then it is not possible to estimate the p_{ijk} 's for those years. In this situation Honma (1974) invokes the assumption that the temporal and spatial distribution of the stock is constant each year, i.e., $p_{ijk} = p_{jk}$ for all i , and suggests estimating the p_{jk} 's using data from "standard" years when coverage was relatively complete. Supposing there are a_{jk} "standard" years when the $(jk)^{\text{th}}$ stratum was fished, we estimate the average p_{jk} for that stratum by

$$\hat{p}_{jk} = \sum_{i=1}^{a_{jk}} \hat{p}_{ijk} / a_{jk}$$

where $\hat{p}_{ijk}$ is given by (8).

In practice, where there are a sufficient number of "standard" years we usually require that a_{jk} exceed some specified minimum value (e.g., $a_{jk} > 2$) to reduce the effects of extreme observations. If a_{jk} does not satisfy this condition we ignore observations from that stratum. [It is clear that the " j^{th} " fishing zone in one year may not be the same as the " j^{th} " fishing zone in another year; similarly for fishing seasons. But it is understood that in computing a particular $\hat{p}_{jk}$ we must use statistics from the same zone and season.]

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THE CALIFORNIA TO HAWAII ANCHOVY TRANSPORT PROJECT

Donald C. Aasted
Southwest Fisheries Center
National Marine Fisheries Service, NOAA
Honolulu, Hawaii 96812

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ABSTRACT

The skipjack tuna fishery in the State of Hawaii has had limited growth partially because of inefficient and time-consuming methods of capturing bait. The baitfish resource in Hawaii is limited in quantity and experiences fluctuation during peak fishing periods, adversely affecting the catches of the local Hawaiian skipjack tuna (aku) fishing vessels.

Supplying a substitute or alternative bait could significantly reduce the fishing pressure on the limited local bait supply and provide an abundance of live bait during the summer fishing season, affording greater fishing effort and efficiency.

In an effort to alleviate this problem, in 1973 the National Marine Fisheries Service Southwest Fisheries Center in Honolulu, Hawaii designed and developed an anchovy transport project to import baitfish from California to Hawaii. This project was carried out with the aid of an advisory ad hoc baitfish committee comprised of representatives from Federal and State Governments, industry, and the University of Hawaii.

The 4-yr project experienced both failures and successes. The shipments of baitfish were accomplished via Matson Navigation Roll-On/Roll-Off vessels originally based in Long Beach, California. Shipping trials were conducted early in hopes of providing the local tuna fleet with much needed baitfish along with experimentation. Testing and modifications of the systems were done during shipping trials.

After a year of unsuccessful shipping trials, shoreside experiments were conducted to determine optimum loading densities and preferred bait handling methods.

Poor quality bait and the moving of the Matson vessels' departure point to Oakland prompted moving the baitfish project to Tiburon. In Tiburon, a series of comprehensive studies were made and optimum loading densities and bait handling methods were produced. An evaluation of the problems with the transport tank unit was conducted. It was determined that inherent problems in the original tank design were too complex to correct, and a completely new transport system was designed and constructed.

A series of docksite experiments was conducted to study the new system and evaluate its carrying potential and the effectiveness of its life support systems. Experimentation with the new system proceeded with a high degree of success, but the project was eventually overwhelmed by the ³lack of a reliable bait supply in San Francisco Bay, and was terminated.

INTRODUCTION

The commercial skipjack tuna, Katsuwonus pelamis, fishing industry in the Hawaiian Islands and the central and western Pacific has been limited in growth and development by the scarcity of live bait. The Hawaiian skipjack tuna fishery, with an annual ex-vessel value of over \$2 million, experiences fluctuations in landings ranging from 2.3 thousand metric tons (MT) to 7.5 MT with an average over the last 28 yr of 4.3 thousand MT. This fluctuation is the result of several factors, the most significant being the unreliability of a continuous supply of live bait during the peak months of the Hawaiian fishing season. The seasonal availability of the Hawaiian baitfish, nehu, Stolephorus purpureus, varies greatly during the fishing months and the supply is insufficient to allow maximum fishing effort by the existing skipjack tuna (aku) fleet. While skipjack tuna in the Pacific is basically an underutilized resource, further expansion and development of the fishery is dependent upon a substantial increase in the available bait supply.

DEVELOPMENT OF THE PROJECT

In 1973, the Honolulu Laboratory of the National Marine Fisheries Service, NMFS, Southwest Fisheries Center, began a feasibility study to determine if importation of an alternate baitfish, the California anchovy, Engraulis mordax, was possible physically and economically, and acceptable to the local Hawaiian pole-and-line fisherman as a supplemental bait. The main thrust of this program was to develop technology and ancillary requirements for successfully holding and transporting California anchovy to

Hawaii. The California anchovy was chosen as the supplemental baitfish to be utilized in Hawaii for several reasons. It is found off the California coast in great abundance, and has been proven to be a hardy baitfish. This bait is utilized extensively by west coast pole-and-line fishing vessels and sport boats with great success.

The development of the baitfish feasibility study program began in early 1973 in California with the gathering of information on bait abundance, seasonal availability, and bait suppliers. Inquiries (to California Department of Fish and Game) were made to determine possible legal drawbacks concerning our proposed project. None of the aforementioned became a problem, and the real problems of handling and shipping bait were approached.

Various methods of shipping the baitfish were explored. Barges, baitboats, and L.A.S.H. (Lighter Aboard Ship) ships were eliminated basically on cost factors, handling problems, and logistics. A form of containerized fish transport tank seemed the most feasible approach, and the Matson Navigation Lines Roll-On/Roll-Off (RO/RO) system looked the most promising. This system involved the use of a mobile trailer (in our case a tanker trailer) which could be loaded with fish and water at a dock area, loaded aboard a ship, and transported to Hawaii. The fish on arrival in Honolulu would be unloaded into holding pools at the NMFS facility at Kewalo Basin for distribution to local aku vessels for fishing trials. The transport trailer would then be returned to California on the same ship for the next shipment.

Matson Lines RO/RO vessels are the fastest freight ships available, having a transit time from California to Honolulu of only 4 days. Live baitfish could be shipped with fast-scheduled regularity.

DESIGN AND CONSTRUCTION OF THE TRANSPORT TRAILER

During the development of the baitfish transport system, bait in Hawaii was scarce, and increasing demands by industry to expedite shipping of baitfish from California were heard.

With the pressure from the fishing fleet for bait and with minimal initial funding, the first baitfish transport system was generated. For reasons of both economy and speed, it was decided by the members of the baitfish project team to utilize a ready-made tanker trailer and to modify it structually to accommodate live anchovy while providing it with a life support system.

The beginning search for ideas brought to light a similar effort undertaken by the NMFS Northwest and Alaska Fisheries Center, Seattle in the transport of live juvenile salmon (Smith and Ebel 1972).

Comparable systems were designed for our tanker trailer with the realization that, while salmon are considered to be very hardy fish that can withstand considerable amounts of handling with low mortality, we were dealing with an animal that is exposed to weakness through red tides, stress, and disease through loss of scales, and considerably more scale loss, effluent, and slime accumulation from handling and being held in captivity.

In 1973, a surplus 5,000-gal military fuel tanker trailer was acquired for the project. Research was conducted on the physiological requirements of the California anchovy and a detailed life support system was developed. It consisted of a recirculation pump, filter system, injected air and induced oxygen, interior lighting, and flowmeters.

The system had two modes: a closed circulation circuit for periods when the trailer was to be transported on the highway, and an open circulation circuit for periods when the trailer was at a dock area for experimentation and loading, or in transit to Hawaii aboard ship.

The transport trailer was divided into three major compartments by two separating bulkheads. These dividing bulkheads each had 20 in. holes in the center allowing water to flow between compartments. Three large hatches, two with small scuttle hatches and one with a large plastic viewing port, were installed over the top of the compartments for easy access and monitoring. The complete tanker trailer was sandblasted and coated with nontoxic primers and epoxy finishes. The interior paints were of a green color and the exterior was painted gloss white.

The interior lighting consisted of two low light level underwater bulbs tinted green, and mounted on the inside top portion of each compartment. Plumbing lines were constructed from polyvinyl chloride (PVC) when possible, and all components to the life support system were chosen for minimal toxicity. The system was mounted on the rear of the trailer on a specially-built platform. The transport trailer was essentially completed in late March 1974, and was tested by hauling

a load of threadfin shad, Dorosoma petenense, another experimental Hawaiian baitfish, from Wahiawa Reservoir to the facility at Kewalo Basin, a distance of approximately 20 mi. The test results were considered satisfactory.

On April 1, 1974, the tanker trailer was transported to the west coast via a Matson Lines RO/RO vessel with an accompanying attendant to check out the various systems and maximum water flows aboard ship. All systems proved operational under these trial conditions, and water flows could be maintained to 400 gal/min.

On April 6, 1974, the transport trailer arrived in Los Angeles and was taken to the Battelle Research Foundation dock in Long Beach. This Long Beach facility was selected as the site of our experiments because of its strategic location, being near the entrance to the harbor and the baiting area, while being secluded and protected from vandalism.

Simulated trial shipments

Simulated trip experiments were conducted at Battelle's dock prior to shipping the first load of baitfish to Hawaii. These experiments were conducted to uncover potential problems, and also to observe results of loading bait directly from the catcher vessel into the transport trailer, and "resting" the bait before shipping.

The method utilized to transfer the bait from the catcher vessel to the transport trailer was the traditional Hawaiian "bucket" system, in which a mixture of baitfish and water are dipped from the baitboat fish well, passed up by hand from the boat to the dock, then further up to the

top of the trailer and unloaded into the open hatch (a distance of approximately 20 ft at Battelle's).

Initial problems

During the first trip simulation experiments, several problems developed. The seawater pumping system for circulating the water through the transport tank was not powerful enough for the higher-than-anticipated head distance, and the final output was far lower than expected, producing poor circulation and a low rate of water exchange within the tank.

The first batches of baitfish, although healthy when loaded into the transport tank, developed the "red-nose" syndrome. This condition is caused by the fish inadvertently running into the sides of the tank and damaging their noses. This damage turns the nose red with blood and leaves the fish in a moribund condition.

Another problem was encountered during the loading of the fish from the catcher vessel on windy days. Considerable surge developed alongside the dock, and coupled with the height which the bait had to be lifted created a serious problem. Several times the bait dealer could not deliver because of the surge.

The transport trailer similar in design to the salmon unit utilized a suction screen located in the center of each compartment to clean the water, but only in the recirculation mode. Dead fish, feces, scales, and slime built up on the bottom of the tank compartments creating areas where fish could contract disease from foul water.

This problem was initially solved by using a swimming pool cleaning siphon system, which was moved around the bottom of the tank compartments by its long handle. Access to the inside was through the three large hatch openings at the top of the tank. At the time, this was sufficient to keep the bottom of the tank compartments clean.

It was readily noticeable while cleaning that the dead fish would accumulate in corner areas in "dead spots" caused by poor circulation and tank configuration.

Two simulated trip trials were conducted at Battelle's dock, each with fairly light loads of bait. Each trial lasted 4 days. The best trial utilized an estimated 160 kg (350 lb) of bait loaded into the tank and resulted in 64% survival.

Trial shipments from Long Beach

Six trial shipments were conducted from Long Beach to Honolulu between April 1974 and March 1975.

The first trial shipment

An estimated 250 kg (550 lb) of bait was bucketed into the transport trailer for the first shipment. These fish were loaded 2 days prior to shipping, giving them a "resting" period to settle them down and orient them to the tank. On April 18, the first shipment to Hawaii departed aboard the Matson Lines vessel, Matsonia. This load, deliberately made light to test the system, arrived in Honolulu on April 22. The trailer was hauled to our Kewalo Basin facility and unloaded, again using the bucket system.

An estimated 80 kg (180 lb) of bait survived the trip, and many of these fish showed signs of the "red-nose" syndrome.

During the trip, the overboard discharge screens were heavily clogged with fish scales thought to be lost during the loading period. On the trip from Battelle's dock to the vessel, the life support system operated on the closed system. The filter system became clogged with scales at that time, reducing the efficiency of the support system.

The return to California of the transport trailer was delayed as further work on it was carried out in Honolulu. It was fitted with an experimental bottom siphoning system to aid in removal of dead fish and detritus and increase water circulation. This experimental siphon unit was to be tested after returning the trailer to California.

The demand for baitfish by the local aku fleet was so great during these trial periods that bait could not be expended for testing the transport trailer in Hawaii.

The siphon system consisted of rerouting the overboard water discharge lines to a pickup point on the bottom of the tank compartments. The lines comprised a down pipe with a tee section at the bottom and two pipes leading off in opposite directions, the ends of which were plugged. Narrow slots were made in the bottom of these pipes to allow water and dead fish to be picked up with the circulating discharge water and removed from the tank.

Upon completion of this modification, the trailer was returned to California for another trial shipment.

The second trial shipment

Bait was again delivered to the transport trailer at Battelle's dock and bucketed directly into the tank. During the resting period of the fish prior to shipping, the new discharge line suction system became clogged with fish, causing overflowing of the tank.

Slots in the lower pipes were widened. Again problems developed, and the dead fish extractor proved to be a live fish extractor as well. The transport trailer was loaded with an initial 725 kg (1,600 lb) of bait 4 days prior to shipping, and topped off 1 day before shipping with an estimated 250 kg (500 lb) of fish.

The "red-nose" syndrome was again present, and with the siphon problems still not fully solved, the shipping trial was conducted.

On May 23, the transport trailer arrived in Honolulu. An estimated 33% of the bait survived the trip.

The third trial shipment

For the third shipment, engineers were consulted to improve the siphon discharge system in the tank. The bottom portion was replaced with large conical suction heads believed to cut down the suction force allowing just rotten material and dead fish to be ejected from the tank. Loading for this trial took place at a different and lower dock area. During the loading, the filter system again became plugged with scales and could not be cleared. This greatly reduced water circulation, and since the oxygen system relied on circulating water for distribution, it

could not function properly. After returning to Battelle's dock, the circulating seawater system was attached and the filter was flushed repeatedly. Bucketing of bait into the tank was resumed in increments at Battelle's dock over several days. During this period, large wattage lights were installed in an attempt to cure the "red-nose" syndrome. These lights were large bright bulbs which would allow the fish better visibility and hopefully prevent them from bumping into the tank walls. The light bulbs were 100-W, 110 VAC, and potentially hazardous from electrical shock. Low amperage fuses were installed to protect personnel and fish in case of a direct short. The results of installing these larger bulbs indicated that a change of this nature was indeed in order.

The fish schooling behavior was much better and the lights had a salutary effect on the behavior of the fish. They no longer tried to jump out of the tank when the hatches were opened.

The "red-nose" syndrome appeared to be reduced significantly.

Unfortunately, the lighting system could not be kept on while the trailer was on the road, and the "red-nose" syndrome reappeared.

During the acquisition of the fish for this shipping trial, another problem became evident. This was the annual arrival of the California "red tide," an algae bloom that seemed to affect the health of the anchovy. Fish delivered during this aging period looked weaker than the previous loads, and were given less chance for survival.

Approximately 545 kg (1,200 lb) of baitfish were loaded into the transport tank during this trial and on arrival in Honolulu on June 27, an estimated 160 kg (350 lb) or 29% had survived.

Bait aging begun

It was finally concluded that because of high mortality rates during shipping, "aging" of the bait should be undertaken prior to shipping. Two tanks were installed at the end of pier C on the Coast Guard dock in Long Beach for this purpose. This location was also desirable since it was located on a restricted pier area away from the general public. This location was also in the same area as the bait dealers' dock, which allowed better communication.

The tanks were 24-ft swimming pools each holding 13,000 gal of water. The water supply was provided by a large submersible pump lowered into the water from the pier. This pump was powered by electricity and provided each tank with approximately 200 gal/min of seawater.

As determined after the third shipment, bucketing of bait was not an accurate method of measuring weights of fish, and the scoop method was used to load an estimated 900 kg (2,000 lb) of bait into the tanks for aging prior to the next shipment.

This method incorporates a long handled dipnet which is used to take bait out of the catcher boat baitwell in a semi-dry state, and transfer it into the aging tanks. Later, when the transport tank was loaded for shipment, the process was repeated.

It was determined that scooping gave a more accurate estimate of fish weight, and for the rest of the shipments this method of handling bait was used.

Care and feeding of the fish became a full-time problem. Once the fish were loaded into the aging tanks, tank cleaning became a continuous

chore. Dead fish, effluent, and scales began to collect on the bottom, and daily tank cleaning was necessary. After a few days, the seagulls found that we had built a natural feeding station for them, and from then on we were plagued with their presence. The bait aging station was attacked daily, and with the dive-bombing seagulls and their continuous defecation in the water, our fish quality dropped drastically. As the fish were attacked by the swooping birds, they were driven down to the bottom of the tanks into the foul water, exposing themselves to disease.

To protect the fish, plastic netting was stretched over the tanks to keep the birds away, but the birds landed on it, made holes, and resumed the attack. Plastic pool covers were purchased and installed. Within a few days, the covers were dirty and ripped around the edges. The fish were more protected, but not completely. With the tanks covered, underwater lights had to be installed in order to keep the fish from running into the sides. Two light bulbs were suspended in each tank at night, and this seemed to work satisfactorily.

The fourth trial shipment

The 900 kg (2,000 lb) of bait loaded into the holding tanks were aged for 3 wk. During the aging period, the fish were fed daily with #1 trout chow. After aging, the bait was transferred into the transport trailer by the scoop method. Random samples were weighed to determine the accuracy of our weight estimates, and an estimated 600 kg (1,317 lb) of bait was loaded into the transport trailer for the fourth shipment.

Prior to this shipment, the filter system was removed since it was continually clogging with scales and could not be made to function properly.

The unsatisfactory siphon system was also removed and bottom drain and top discharge systems were installed in each compartment to eliminate the effluent problem and remove dead fish as they accumulated on the bottom. This experimental system seemed to work satisfactorily although the configuration of each compartment made it impossible for the system to clean the bottom thoroughly.

The installation of a new lighting system had also been undertaken, consisting of a constavolt-type charging unit, batteries, and larger wattage light bulbs. This system was designed to operate continuously at all times while the transport trailer was holding fish.

When the transport tank was shipped for the fourth experimental trial, it was sent unattended during the ocean crossing.

Since the modifications were untested, and this was the only period for their trial, the top screens were cut open and rubber risers installed to prevent potential disaster. It had been noticed that during the first shipment, the other time these same screens had been used, they clogged when scale loss was heavy. If this were to happen at sea with the tank unattended, the tank would overflow flooding the inside of the ship.

During this shipment, the location on board ship for the transport tanker trailer had been changed for ease of parking and timing for loading. After loading the trailer on the vessel late in the evening, the power supply to the trailer was plugged in to the ship's outlet. The ship's outlet had been incorrectly wired and immediately a short circuit occurred causing the wiring to burn up. After repairing the system, the hatches were opened and it was discovered that the rear tank screen, including the rubber riser, was allowing fish to be discharged from the tank at a rapid rate. The new

location on the ship had changed the trailer level, and the water seeking a new level rose above the rear discharge screen. Without any available repair equipment or any time for corrective action before sailing, the shipment departed on August 7, discharging fish overboard during the 4-day crossing to Honolulu. On arrival in Honolulu, about 410 lb of fish were unloaded from the transport trailer. The surviving fish appeared to be in excellent shape. The bottom of the tank was not covered with dead fish and debris, indicating that a partial correction of the problems had been made.

It appeared that the rest of the fish had been ejected over the side during the transshipment. Since an attendant did not accompany the trailer during the crossing, it was not possible to determine if the discharged fish had been dead or alive.

Optimum density studies begun

After the conclusion of the fourth shipment of anchovies, it was decided that density studies should be undertaken to determine the optimum carrying capacity of the baitfish transport system. During the same period, aging of bait in the holding tanks would be done to eliminate much of the variation in the quality of the bait before proceeding with further trial shipments to Honolulu.

For 3 mo, aging and density experiments were conducted. Problems encountered during these experiments were diseased fish attributed to red-tide, foul water in the pools, and continued harassment by sea gulls. The density experimentation studies resulted in a survival model relating input of anchovy to output or survival during a 4-day simulated shipment. Three experiments conducted in the transport tanker developed eight data points, which were considered sufficient to graph the desired survival model.

These points are shown in Figure 1 and indicate that optimum loading occurs at 795 kg (1,750 lb) input with yield (survival) of 500 kg (1,100 lb) of live fish after a 4-day simulated trip.

The fifth trial shipment

Upon conclusion of the density experiments, trial shipping experiments were resumed. Trial shipment #5 left Los Angeles on November 30 with the tank unit loaded with 743 kg (1,634 lb) as measured by the scoop method, or slightly less than the determined optimum loading density. During the 3 mo of bait aging experiments, the bottom experimental screen drain system was used. Afterwards, while transporting the trailer to the ship for loading, the front bottom screen unit broke loose as electrolysis disintegrated the hold-down weight bolt. Live fish were sucked through the closed circuit recirculation pump and pulverized, contaminating the water with a red scaly fish soup. The problem was discovered after the 45-min trip from the dock to the ship during the loading period. The results were again a poor shipment; the tanker arrived in Honolulu with only 23-kg (50 lb).

The sixth trial shipment

The sixth and final shipment to leave the Long Beach area commenced February 10, and arrived in Honolulu on March 17, 1975.

It became obvious that the recirculation pumping system was inadequate. Due to the poor shape of each compartment, a larger pumping system would still not solve the problems.

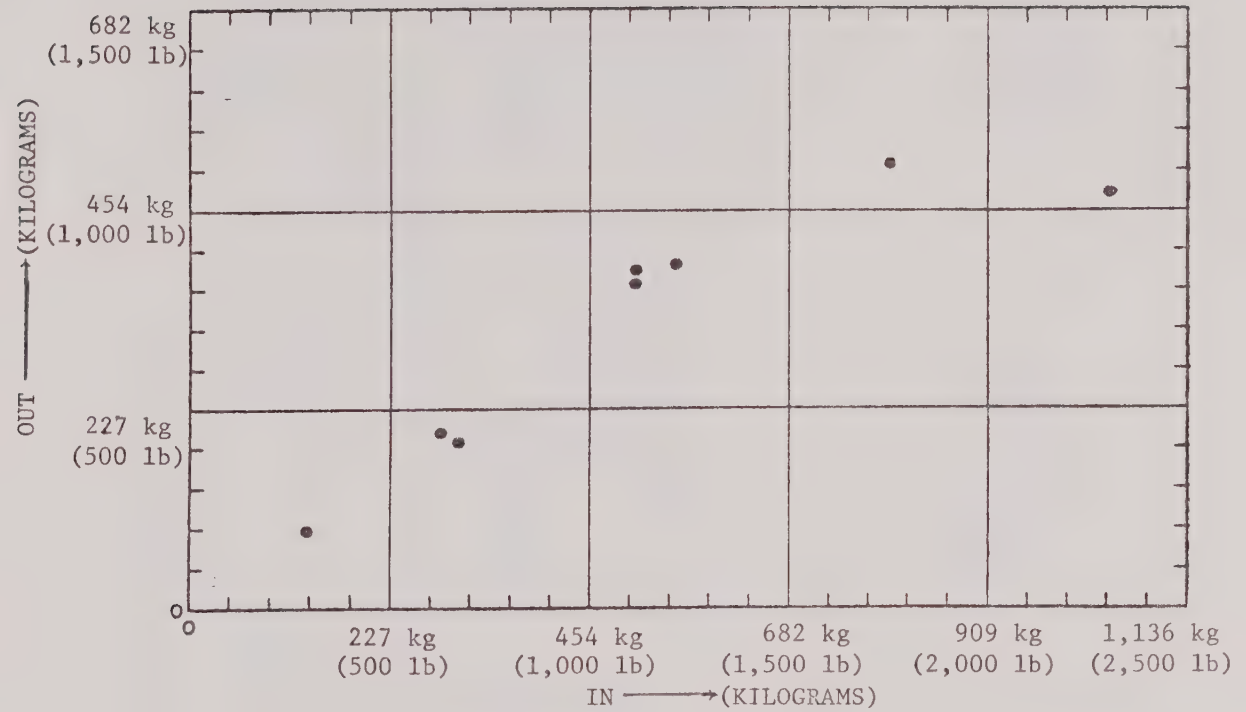


Figure 1.--Output compared to input in bait transport tank after 4-day simulated operation (individual compartment totals converted to full tank-load equivalents).

Table 1.--Synopsis of bait aging experience.

Dates loaded	Input kg	lb	Date unloaded	Output kg	lb	Survival rate (%)	Remarks	Disposition
<u>1974</u>								
9/10, 11	1,364	3,000	9/17	91	200	7	Red tide; poor bait quality	Experiment in tanker
10/9	909	2,000	10/15	909	2,000	100	Healthy bait	Experiment in tanker
10/16	682	1,500	10/15	91	200	13	Disease; poor quality bait	Dumped
10/21	682	1,500	10/27	356	784	52	Disease; many jack mackerel	Experiment in tanker
10/28	909	2,000	10/31	91	200	10	Disease; poor quality bait	Dumped
11/8	909	2,000	11/14	768	1,690	85	Good bait; covered pools	Experiment in tanker (switched off; bait died)
11/15, 18	950	2,090	11/21	448	985	47	Fair quality bait	Experiment in tanker
11/25	1,000	2,200	11/30	728	1,601	73	Fair quality bait	Shipped; lost in transit
<u>1975</u>								
2/18, 21, 24	1,920	4,225	2/27	0	0	0	Fair quality bait; power outage	Dumped
3/3, 13	2,045	4,500	3/17	788	1,734	39	Poor quality bait at shipping time	Shipped 743 kg (1,634 lb); delivered 261 kg (574 lb) to Honolulu
Totals	11,370	25,015		4,270	9,394	416		

The existing pumping system was removed, and 10 air stones were installed in the bottom of the transport tank. A complete set of screens fastened to the bottom was installed to drain off the muck from the bottom of the tanker. With the water going out both the top and the bottom, this provided better circulation within the system.

Prior to shipping, the first batch of hardy, well-aged anchovies were inadvertently killed the night before shipping. Another load of bait was delivered for aging, but the quality of this batch of bait was not as good, and during aging mortality was comparatively high. A total of 743 kg (1,634 lb) of this "less than perfect" bait was loaded into the tanker for shipment; 261 kg (574 lb) were delivered live in Honolulu.

Baitfish transport experiments moved to Tiburon

Continued problems with high mortality of the baitfish at the aging station in Long Beach contributed to the failure of the transport project up to this point. Poor bait and poor water quality appeared to have been the major causes of this mortality.

In April 1975, the baitfish committee recommended withholding further aging and shipping trials until the actual causes of the heavy mortality could be investigated. This would be done at the NMFS dock area in Tiburon, California, located on San Francisco Bay. The water quality in this location is far superior to that of Los Angeles Harbor, and an abundance of small anchovy is reported to occur there during the summer months.

During this same period, Matson Navigation Company informed the NMFS that their RO/RO vessels were to be moved from Los Angeles Harbor to the new Matson shipping terminal at Oakland.

By August 1975, the aging station in Long Beach had been moved to the NMFS Tiburon dock area. This new station was composed of two large 13,000-gal plastic-lined swimming pools, and a complex of twelve 400-gal aluminum holding tanks in which the experiments were to be conducted. Seawater was supplied to the pools and tanks by two submersible pumps providing separate water supplies to each system. A lighting system was installed above each tank to avoid the reoccurrence of the "red-nose" syndrome, and predator screens were fastened over the tops.

On September 4, 1975, the tank farm was completed, and factorial experiments which had been designed earlier were begun in order to assess the effects of bait quality, oxygen levels, salinity, handling methods, and loading densities on survival rates.

From September 15 through November 4, 1975, a series of five experiments were conducted. During this period, batches of bait that were captured and delivered by local bait boats varied greatly as to size and quality. Three methods were tested to handle the fish: pump, dry scoop, and the Hawaiian bucket system. The bucket handling method caused less scaling and was preferred over the other two, although it allowed a greater margin of error when estimating the weight of the fish being transferred.

Based on the density experiments, optimum holding density with the least mortality in a 400-gal test tank was 0.08 kg (0.18 lb) fish/gallon. Details on the above may be found in a preliminary report on the baitfish transport project by Stanley Smith and Robert Hoffman, 1975.

After the completion of this series of experiments, further experimentation was curtailed until after the winter season, November through March. With the seasonal drop in water temperatures and salinity, the fish are apparently weaker and more susceptible to stress. Further experimentation in the winter was not considered representative of normal conditions since shipments would be made from April through September, which is during the skipjack tuna fishing season in Hawaii.

BAITFISH PROJECT 1976--NEW MANAGEMENT, NEW METHODS

In January 1976, the baitfish project was reactivated, this time under new management and direction. It was apparent that the basic transport tank system needed extensive modification. Tank configuration, lighting, oxygen, circulation, dead fish extraction, and loading systems all had to be restructured. Previous bait handling methods such as bucketing, scooping, and pumping caused stress and loss of scales to the fish. These methods were also time-consuming and labor-intensive. Bait transfer methods needed to be simplified. Feeding would have to be reduced or eliminated completely. Aging would have to be eliminated or substantially reduced to keep fish from becoming contaminated or diseased prior to shipping. Holding fish on the closed-circuit mode prior to shipping had to be minimized. With these requirements in mind, a completely new baitfish transport system was developed.

Development of the new baitfish transport system

The baitfish project was reactivated under a three-part development scheme: (1) design construction, (2) experimentation (loading and density studies), and (3) shipping trials.

Design theory

The first problem was to develop a new concept in loading procedures which would eliminate virtually all handling of the baitfish. Research into the engineering aspects of the problem resulted in a completely new approach to loading bait into shipping tanks.

It was hypothesized that two large circular tanks could be constructed with a combined carrying capacity equal to that of the previous system. These tanks could be lowered into the water one at a time, loaded with live fish and water in one movement similar to the bucket system, and replaced on the trailer ready for shipment.

If this were possible, the concept of holding bait in an open, free circulating bait barge could be used, allowing the fish to utilize natural feed and oxygen. This barge could then become the loading vehicle into which the tanks could be lowered. The fish could be transferred directly from the water into the tanks for shipping. If this method were feasible, handling of the bait would be kept at an absolute minimum and survival rates at their maximum.

Tank design and construction

An extensive review of the problems encountered with the previous transport system aided in the development of the new transport tank design. Tank configuration, circulation, sludge build up, and loading methods were analyzed and made the basis for the development of the new tanks. Two 2,500-gal circular tanks were designed with conical bottoms and tops for maximum self-cleaning capabilities. Inlet and discharge water systems were incorporated to provide good circulation throughout

the entire tank. Lighting and oxygen system were also integrated into the tank system to provide maximum life support for the baitfish. The tanks were designed to be lifted fully loaded, each weighing 14 tons.

In early May 1976, preliminary drawings were submitted to a structural architect and engineer for review and analysis. A duplicate set of working drawings was made and distributed to commence construction of the tanks.

During June and July 1976, the transport tanks underwent construction in Hawaii, complete with contractor delays and material acquisition problems. The tank shells arrived in Tiburon in mid-August and installation of the various life support systems and plumbing commenced. By mid-September the majority of the construction had been completed with one tank finished and tested. All systems worked well and water flow through the single tank was measured at 150 gal/min.

Trailer

For carrying the tanks, a used, heavy-duty military trailer was located in California and delivered to the Tiburon Laboratory for modification. The trailer was stripped of its excess metal parts and modified to accommodate the plumbing, circulating water, lighting and oxygen systems, and flow meters. The front of the trailer became the housing area for a diesel generator which powered a submersible pumping system mounted on the rear. The generator and pumping units enabled the trailer and tanks to be self-contained at all times and provide a continuous flow of water to the fish. The generator also provided electrical power to the battery charging unit which, in turn, powered

the 12-VDC lighting system. This system utilized two 12-V batteries connected by long cables to the tanks, allowing the interior lighting of the tanks to be on continuously.

The oxygen supply cylinders were also housed in the front section of the trailer and, similar to the lighting system, were connected by long hoses to the tanks, providing a continuous supply of oxygen as required. A recirculation pump was also mounted in this area, which provided water flow through the tanks during the closed-circulation mode periods.

Bait receiver barge

A bait receiver barge built for holding anchovies was located in San Diego and made available to the project on a lease basis. A tug boat towed the barge to San Francisco and delivered it to our Tiburon Laboratory pier where a specially designed mooring had been placed. To gain maximum water flow through the barge for good circulation, it was located on the end of the pier in a current area. The mooring was so placed as to keep the barge away from the pier and safe from damage. The barge was rigged with underwater lights which operated from a power source on the pier. These lights promoted schooling behavior in the fish prior to their being loaded into the tanks and also alleviated the chance of their developing the 'red-nose' syndrome. The barge was also outfitted with predator grates on the top, keeping the birds away from the fish. Loading and crowder nets were designed to fit within the barge to capture the bait for loading into the tanks.

EXPERIMENTATION

Experimentation with the new baitfish transport system was designed as a four part scheme. The first part was the development of general procedures involving bait acquisition, tank and net handling, and loading techniques.

It was decided that a commercial bait boat would capture the bait, wet brail the fish into its baitwells, and transport them to the bait barge moored at Tiburon. The bait would then be unloaded by a flume method, which allows bait and water to flow out of the baitwell into the barge with little damage to the fish. After holding the bait for a short time (aging) to observe their physical condition, the barge would be moved to a position alongside the dock at the Tiburon Laboratory for transfer of the bait to the transport tanks. The two transport tanks situated on the trailer would be positioned on the dock adjacent to the bait receiver barge. A large crane would lower the tanks, one at a time, into the barge to be loaded with bait. While lowering a tank into the barge, a water supply hose would be attached, and also, the end of a holding net into which all the fish were maneuvered would be attached around the open side door. After the net was attached, the tank would be lowered into the water, and as the water rose to the door, the fish would be crowded toward the entrance. While the tank was being lowered, water would be pumped in to aid in its submersion. Once the water filled the tank within 6 in. of the door opening, the tank would be lowered rapidly allowing fish and water to enter through

the open door. During this process, the net containing the bait would be drawn tight toward the door permitting all the fish to flow into the tank.

After the tank received the fish, the inner door would be closed and the tank filled completely with water. The net and water supply hose would be removed, the outer door closed, and the tank operated on the closed-circulation mode with lights and oxygen being supplied from the trailer. The filled tank would then be lifted from the barge and relocated on the trailer. The open-circulation mode would then be applied, giving the confined fish adequate life support. After duplicating the operation for the second tank, the baitfish transport system would then be ready for an experimental period at the Tiburon dock, or be ready for loading aboard ship.

The second area of concern was the critical estimating of the weights of fish to be loaded into each tank. Since the new system did not incorporate bucketing or dipnetting of the bait, visual weight estimation was to be used. To accomplish this, the fish were crowded into a holding net in half of the barge. The fish in the net were then split into two parts by sectioning the net, which involved raising a chain placed across the bottom of the barge. After the chain was drawn up and the fish divided, each section of the net was drawn up (drying up the net) and the weight estimated. By lowering the dividing chain, the fish could be adjusted to approximately equal portions on either side. Each half of the fish would be loaded into each tank. After several experimental trials, weight estimation would become more accurate.

The third portion of the scheme was a series of 4- to 5-day experimental simulated shipping trials at the Tiburon dock. These trails were designed to analyze the tank system for performance to allow modifications to be made if necessary prior to actual shipping trials. During these loading trials, dissolved oxygen, water flows, fish swimming behavior, and physical condition of the fish would be monitored.

The fourth and most critical experimentation to be done in the scheme was density loading of the fish. Progressive density studies were to be carried out during the experimental trials to realize the maximum sustainable density loading of the fish required for shipment from Oakland to Hawaii.

Preliminary baitfish acquisition problems

During the baitfish tank experiments at Tiburon in 1975, it became evident that there was a tremendous amount of rivalry between the only two baitfish dealers located on San Francisco Bay. While engaging in the experimental tank farm loading and density studies, the participating bait dealer indicated that if we accepted bait from the other firm, he would not make further deliveries to the tank complex.

The following year, to commence experiments with our new transport system, the same bait dealer was notified to begin delivery to our bait receiver barge. For many days, in spite of repeated efforts, he would not make contact with Laboratory personnel. Finally, it was decided to contact the second bait dealer to see if he would be more

cooperative and supply our needs. He, too, indicated that he would deliver bait, but if we went back to the previous dealer he would cancel his obligation to us.

Our second bait dealer supplied us with baitfish on time during the 1976 period of the transport trailer experimentation.

1976 Simulated shipping trial

In mid-September 1976, to expedite the project, it was decided to conduct the first experiment with the one completed tank. The barge had been filled with baitfish from the dealer's catcher vessel, and an estimated 635 kg (1,400 lb) of aged anchovy were available to conduct this experiment.

On September 22, the barge was positioned for loading fish, and the large crane manipulated the transport tank. Except for some minor adjustments with hoses and lines, the first loading of fish into the tank proceeded with little interruption. The actual loading time took 20 min. After the tank was returned to the trailer, it was shifted from the closed to the open-circulation mode to commence a simulated 4-day crossing from Oakland to Honolulu.

Since this experiment was the first time a visual weight estimation of this type was to be conducted, our weight estimation was considerably in error. To insure an accurate accounting of all fish that were loaded into the system, a fine mesh net captured all fish that were discharged from the tank. This procedure was utilized during all the experiments. Upon completion of the experiment, all remaining

live fish were weighed dry in a bucket, and combined with the weight of the discharged fish to give the final results.

A total of 200 kg (440 lb) of anchovy survived the one tank experiment with only a 2.2% mortality.¹ The condition of the fish was satisfactory with no "red-nose" syndrome or disease in evidence.

After loading the bait from the barge into the tank for the experiment, a second load of anchovy was ordered and an estimated 900 kg (2,000 lb) delivered.

During the week of aging in the seawater-filled barge, the fish showed signs of weakness and disease. This load was discarded and another load was delivered to the barge. Again, this time the next day, the bait was weak and sick looking. It was concluded that this was the beginning of the period when anchovy become stressed easily because of annual physiological changes. The decision was made to mothball the program until spring, when the fish would be more viable and actual shipping would be undertaken.

Simulated trials, trial shipment, and termination

The baitfish project was resumed in March 1977 with the demothballing of the baitfish receiver barge at Tiburon. The large iron grates were reinstalled, and the lighting system replaced making the barge ready to receive bait.

¹Memo, from Donald Aasted to Richard Shomura, Director, Honolulu Laboratory, dated October 7, 1976, Subject: Report on the first trial run of a simulated bait shipment to Honolulu from San Francisco.

The bait dealer was notified both verbally and in writing stating our intentions to continue the baitfish project. He agreed that bait delivery would be made on the same basis as the previous year, and delivery would be made as soon as bait became available. Personnel from the Tiburon Laboratory made repeated contact with the bait dealer as to bait availability, size and location, and expected delivery dates, and although other sources indicated that bait was available, we did not have a delivery. Finally, in June, our bait dealer indicated he could deliver bait, and with this notification, the baitfish transport system was again readied for experimentation on the Tiburon dock. Again, we waited for our first delivery of baitfish. Finally, on July 27th, 5 mo after our initial contact with the bait dealer, we received the first load of baitfish for the year.

First simulated shipping trial²

After 1 wk of aging bait, the first experiment was conducted on August 2, 1977. During the crowding portion of the loading operation, it was noticed that the amount of bait within the barge was considerably less than what was estimated delivered the previous week.

²Memo, from Tom Barnes, Tiburon Laboratory, to Director, Honolulu Laboratory, dated August 9, 1977, Subject: Progress report, first bait holding trial, 1977.

A loose plank was discovered on the bottom of the barge allowing predators to swim in and baitfish swim out of the large hole. Since the amount of fish left in the barge did not warrant the use of two tanks for an experiment, the forward tank was filled with fish and water, and the rear tank filled with water and used as control to monitor oxygen and temperature levels. The forward tank was loaded with 312 kg (687 lb), and 291 kg (641 lb) or 93% survived the 5-day simulated shipping trial. Loading problems were minor and easily adjusted. The condition of the fish was excellent, with no 'red-nose' syndrome or disease present.

Second simulated shipping trial³

On August 23, our second delivery of bait for the year arrived, and again the fish appeared in good condition and were aged for 1 wk. Two modifications were made for this trial: one was a different fish guard over the bottom discharge area where live fish were being caught in the discharge collecting system. The second modification was an increase in plumbing diameters to increase water flow to their maximum. Water flow increased from 150 to 195 gal/min in each tank providing an ideal flow for the system and for fish swimming speeds.

It was decided to load both tanks although the amount of bait in the barge again appeared considerably less than the 909 kg (2,000 lb) delivered. The density in each tank would not be as great as required

³Memo, from Tom Barnes, Tiburon Laboratory, to Director, Honolulu Laboratory, dated September 16, 1977, Subject: Progress report, second bait holding trial, 1977.

for a density study, but prior to this we had not used both tanks, and felt it necessary to go through the entire loading procedure testing both tanks under loaded conditions.

- Both tanks were loaded with 343 kg (755 lb) divided equally between them and the survival rate was 99% during the 5-day experimental period. The excellent survival rate was attributed to the light density load in each tank, and although still not perfected, to the modified bottom fish guard.

Third simulated shipping trial⁴

On September 11, 1977, an estimated 909 kg (2,000 lb) of bait was loaded into our receiver barge. To try and eliminate an escapement from the barge and gain knowledge as to length of time needed for aging, the fish were loaded into the transport system 3.5 days after delivery to the barge. Again, the amount of fish in our barge, when crowded into the loading net, appeared much less than what was estimated delivered. The loading crew estimated that we had 455 kg (1,000 lb) captured in the net. This amount was determined to be ample for a maximum density loading for one tank, so the front tank was filled with 432 kg (953 lb) of live fish. A calculated 406 kg (894 lb) survived the trial period with an outstanding 94% survival rate.

During this trial period, a few live fish were still being discharged daily from the bottom fish guard. Further design and experimentation were necessary.

⁴Memo, from Tom Barnes, Tiburon Laboratory, to Director, Honolulu Laboratory, dated September 23, 1977, Subject: Progress report, third bait holding trial, 1977.

Table 2.--Synopsis of simulated shipping trials.

Trial Period	Input (kg)	Tank used	Output (kg)	Remarks (% survival/condition)
<u>1976</u>				
9-22/26	204	Tank 1	200	98% - excellent health
<u>1977</u>				
8-2/7	312	Tank 1	291	93% - excellent health
8-31/9-6	343	Both	340	99% - excellent health
9-13/19	432	Tank 1	406	94% - excellent health

Trial shipment and termination of project⁵

Because we lacked a reliable supply of anchovy in San Francisco Bay, the decision was made to terminate the baitfish project at the end of September.

On September 18, the bait dealer delivered an estimated 909 kg (2,000 lb) of anchovy into our bait barge. Originally, this bait was intended for a fourth experiment prior to actual shipping trials to Honolulu, but in light of the impending termination, it was held for use during the trip returning the transport tank system and equipment to Hawaii. It was decided to make one attempt to ship a load of baitfish to Hawaii although the system was not yet perfected. The bait dealer was asked to "top off" the bait in the barge prior to departure. He was unable to accommodate us, and the shipment was made with only a partial load of bait.

During this period, our generator unit arrived and was installed. This unit was the key to making our transport trailer mobile and self-supporting. It also allowed the installation of the needed dual recirculation pumps, but since time was now short and funding limited, this circulation system was not installed.

The open-circulation submersible pump was mounted on the trailer suspended from a large davit, and the various other components were made ready for the shipment to Hawaii.

⁵Memo, from Donald Aasted to Richard Shomura, Director, Honolulu Laboratory, dated October 31, 1977, Subject: Baitfish project: final report.

On September 30, 1977, the baitfish transport trailer, the partially loaded bait receiver barge, and personnel moved to the Matson shipping terminal where the fish were loaded into one transport tank. The weight of the fish loaded into the front tank was estimated at 500 kg (1,100 lb). The second tank was filled with seawater to act as control while monitoring the system.

Loading at the Matson dock proved to be a simple operation, and the baitfish transport trailer remained self-contained for 5.5 h before it was finally loaded onto the ship. Mortality during this period was minimal; three fish were ejected from the discharge system. During the loading of the transport trailer on the ship, the recirculation pump delivered only 50 gal/min through the bait filled tank (this system was to be replaced with the dual high-volume pumping system), not enough to create good circulation within the tank. After loading, the ship's seawater system was connected, and an estimated 1,000 gal of stale, contaminated water ran through the tank system. This seawater system was reportedly used prior to our shipment, but unfortunately, it was a different hose connection used further aft in the ship, and it did not flush out the plumbing in the forward section of the ship where the trailer was located.

With the poor circulation during loading and the poor quality water circulated through the tanks, the fish began to die and continued throughout the night at a rate of at least 23 kg/h (51 lb/h). Surviving the following day was about 212 kg (468 lb) of bait, and after the

4-day crossing to Hawaii, 204 kg (450 lb) was delivered in Honolulu from the one tank.

Reasons for lack of adequate bait supply

As indicated in early 1977, our new bait dealer did not deliver bait to our receiver barge for several months. It was learned later that this was a result of several factors, chief among them being a change in environmental conditions in California, believed to affect the amount of bait available within San Francisco Bay. This change had also undermined the dealer's primary business of freezing bait for sale. During the summer, delivery to our barge was again put off due to the large number of albacore boats entering San Francisco Bay requiring bait from our dealer. Since both of these operations provided considerably more profit for fish delivered, the California to Hawaii baitfish project suffered from low priority.

Baitfish transport shipment costs examined

Costs incurred during the shipment from Oakland to Hawaii originating on September 30, 1977 are as follows:

Purchase of live bait	\$ 400.00
Tugboat services - Tiburon to Oakland and return (move barge)	825.00
Crane service at Matson	375.00
Shipment to Hawaii	1,750.00
Rider on ship	267.00
Crane service in Honolulu	<u>395.00</u>
	\$4,012.00

Crane and tug services can be reduced significantly if the whole operation is conducted in the Richmond/Oakland area. Matson Lines has indicated that utilization of their giant overhead cranes might be possible for loading and unloading of the tanks. The suggestion was also made to help defray shipping costs by loading the tanks with a return cargo. Lobsters, fish, and other live or manufactured products could be exported to the west coast via these tanks.

Matson has also proposed a renegotiation of shipping charges to aid in making this specialized shipping a viable operation.

CONCLUSION

The final design for a baitfish transport system to import live anchovy from California to Hawaii, as evidenced by the few simulated trials conducted, appeared to function well.

Optimum loading density is still an amount which has not been verified, but 455 kg (1,000 lb) per tank seems to be a realistic figure, with 90% survival rate or better. The simulated trials never approached thresholds that would cause mortality in the anchovy. Further experimental examination of the system will produce more conclusive results.

Bait weight estimation without direct handling is a serious problem. Even experienced bait dealers are not as accurate as they would have you believe. Estimating the weight of fish within the loading net appears to be the easiest method and the least harmful to the fish. Only practice and net markings will refine this method of weight estimating. Undoubtedly a sophisticated electronic unit is or can be

devised to count fish and give accurate weights without handling, but at present such a system would be very costly or would require capital expenditures. A large crane is at present the only method available to lower the tanks into the bait barge for filling. Matson has indicated there is a possibility of using their large container cranes to load and unload the tanks of fish. This would solve this problem and also reduce the cost of shipping. If this system is used, it gives rise to the possibility that all loading and unloading of the baitfish could be conducted at the Matson container yards at both ends of the shipment, making it necessary to hold the baitfish on the closed-circulation mode for only a few minutes. Problems solved during the development of the new transport system were directly related to the decrease in mortality of the bait. Eliminated were direct handling, the 'red nose' syndrome, and diseased fish which attributed to the greater mortality rates.

The great distances and length of time fish had to be held on the closed-circulation system were reduced to a few minutes. Aging of the bait was reduced to a few days, and this was finally just an inspection period to evaluate the health and condition of the bait. Labor-demanding tank cleaning, fish feeding, and bucketing of the bait were also totally abolished.

Given good tank configuration, circulation, lighting, and a clean environment, the capturing, holding and shipping of anchovy in containers appear feasible. Only further experimentation and shipping trials will provide conclusive evidence to this theory.

This report does not reflect a detailed economic feasibility analysis. Any such study will require an in-depth analysis of three major components: (1) the supply or availability of bait on the west coast, (2) the capital and operating costs of the transport system, and (3) the demand for the delivered product in Hawaii. Such an analysis is an entirely separate report in itself and should be undertaken after the baitfish transport system is proven a viable system for transporting baitfish from California to Hawaii.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the staff members of the Tiburon Laboratory of the National Marine Fisheries Service for their assistance during the second phase of this project. I also wish to express my appreciation to my crew, Stanley D. Smith and John Thomas Barnes, who ran the project during my absence at Tiburon and contributed excellent Progress Reports which aided me in documenting this project.

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APPENDIX

Ad Hoc Baitfish Committee

The California to Hawaii baitfish project was advised by an ad hoc baitfish committee composed of representatives from:

National Marine Fisheries Service
Pacific Tuna Development Foundation
Pacific Island Development Commission
Hawaii State Department of Planning and Economic Development
Hawaii State Division of Fish and Game
Hawaii Institute of Marine Biology, University of Hawaii
Department of Economics, University of Hawaii
Marine Programs, University of Hawaii
Sea Grant Programs, University of Hawaii
Tuna Boat Owners Association
Bumble Bee Sea Foods
Hawaiian Tuna Packers
United Fishing Company

This committee reviewed the progress of the baitfish project, advising the National Marine Fisheries Service project members as to course and direction to be taken during the project.

PER CAPITA ANNUAL UTILIZATION AND CONSUMPTION
OF FISH AND SHELLFISH IN HAWAII, 1970-77

Linda L. Hudgins
Southwest Fisheries Center Honolulu Laboratory
National Marine Fisheries Service, NOAA
Honolulu, Hawaii 968L2

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INTRODUCTION

In 1977, the United States per capita consumption of edible (meat-weight) fish and shellfish was 5.82 kg (12.8 pounds). It has been speculated that the per capita consumption of fishery products in the State of Hawaii is considerably higher than the United States average. No studies have been done to verify this speculation. This paper is an attempt to quantify this actual consumption in Hawaii for the period 1970-77. This quantification required computation of the total supply of fish and fishery products available in Hawaii. The total supply was then adjusted to edible weight and divided by the population. The result is that the per capita consumption rate in Hawaii for 1977 was about 77 percent higher than the United States average.

Foreign imports represented, in 1977, approximately 54 percent of the total supply of fish and shellfish in Hawaii. Therefore, a section and tables are included in which these imports are disaggregated by quantity, value, and type of preparation for 1970-77; and by major product and major country of origin for 1976 and 1977.

An effort was made to calculate the per capita figures with the same methodology as that used in Fisheries of the United States where national per capita estimates are published. The units of quantity and measurement in this report are not exactly comparable in some cases. These measurement discrepancies, as indicated in the table notes, should not however, hinder the usefulness of these preliminary estimates.

DATA AND METHODS

The State of Hawaii has three major sources of commercial fish and fishery products for human consumption: 1) local catch, 2) imports from foreign countries, and 3) interstate shipments from the mainland United States. Table 1 gives totals for these sources. Hawaii landings are shown in round (live) weight as reported by the vessels to the State of Hawaii, Division of Fish and Game. Foreign imports and interstate shipments are in net product weight, as recorded at the port by U.S. Customs officials and published by the U.S. Bureau of the Census (1970-77) and the U.S. Army Corps of Engineers (1970-77).

Hawaii per capita utilization (Table 2) is determined using total supply of fishery products without adjustment for beginning or ending stocks, foreign exports or defense

Table 3 purchases. Table 3 gives a comparison of the United States and Hawaii per capita utilization rates. Table 4 gives United States per capita consumption of fish and shellfish as published by the National Marine Fisheries Service. Hawaii per capita consumption in Tables 5-7 is based on pounds of edible (meat-weight) fish. Figures for Hawaii in Tables 5-7 are adjusted for foreign exports of fish and shellfish and shipments of canned tuna and fresh and frozen fish to the mainland United States. Supply of cured fish for consumption includes fish dried, salted, smoked or kippered whether canned or not. Cured supply does not include local production of cured fishery products. Raw inputs for local production are counted under fresh, frozen, or chilled. Supply of canned fish for consumption includes fish of all preparations in airtight containers, most of which are cans.

The State of Hawaii has three variable components of population in addition to the civilian resident population: military, visitors, and foreign in-migrants. Military includes those who are serving in the armed forces and either actually residing in Hawaii or stationed aboard a ship homeported in Hawaii. Since 1971, the military has stabilized at around 6 percent of total de facto population (those actually present in the State). Military dependents are counted as part of the resident civilian population. There are approximately 1.15 dependents per military

member in Hawaii. Visitor population estimated by the Hawaii Visitors Bureau during 1978 was around 9 percent of the total population based on the annual average number of visitors present. Approximately 8 percent of the civilian resident population of Hawaii in 1970 were foreign born persons from China mainland, Taiwan, Japan, Korea, and the Philippines. All of these countries have substantially higher per capita fish consumption rates than that of the United States (U.S. National Marine Fisheries Service, 1978:74). These three components of population may account for over 20 percent of the actual population present in the state at a given time. For this reason, per capita consumption was calculated for various measures of population which would include these groups.

FOREIGN IMPORTS

Imports from foreign countries in 1977 represented 54 percent of the total supply of fish, fishery products, and shellfish in Hawaii. Table 8 gives these imports by year and type of preparation, aggregated over countries. All of these products are those designated for human consumption. Values are unadjusted and reflect customs values. Customs value generally represents a value in the foreign country,

and therefore excludes United States import duties, freight, insurance, and other charges incurred in bringing the merchandise to the United States. This value may not reflect the actual transaction value.

able 9 Table 9 gives imports to Hawaii of fresh, frozen, or chilled fish, and shellfish by major country of origin, quantity, and customs value. Relative rankings of these countries vary between 1976 and 1977. However, the major five countries (New Hebrides, Philippines, Taiwan, Japan, and Panama) are the same for both years. Fiji had no recorded exports to Hawaii in these categories for 1977.

able 10 Table 10 gives imports to Hawaii "in cans or airtight containers." Shellfish and anchovies are the major products. In 1972, the major sardine exporting countries were Brazil, United Kingdom, and Denmark. In 1973, only Denmark is recorded as exporting sardines to the Honolulu customs district which is reflected in the much lower 1973 figure. The category marked "other" in this and subsequent tables represents other species which the U.S. Customs aggregates under the heading "not elsewhere specified."

able 11 Table 11 reflects edible fishery products by major type of preparation. Tuna, fish fillets, and shellfish comprise over 90 percent of the total fresh and frozen imports to Hawaii for 1976 and 1977. The itemized entries under "canned" for 1976 reflect over 60 percent of the total quantity of canned imports to Hawaii and for 1977 over 78 percent. The category "Other fish and shellfish" reflects the sum over type of preparation of the "not elsewhere classified" specifications.

able 12 Table 12 represents estimated per capita consumption of foreign imports by type of preparation, adjusted to pounds of edible fishery products divided by civilian resident population of Hawaii on 1 July of each year.

SUMMARY AND CONCLUSIONS

The tabulated data show that the total per capita consumption of fish and shellfish in the State of Hawaii has been higher than the United States average over the entire period, 1970-77. Specifically, the following conclusions can be drawn about fish and shellfish consumption:

1) United States per capita total consumption has followed a slightly upward trend. From 1973 to 1977, consumption varied between 5.45 and 5.91 kg (12 and 13 pounds).

2) Hawaii per capita consumption for all fish products followed an unclear trend over the period. Consumption declined dramatically from 1972 (11.14 kg (24.5 pounds)) to 1974 (8.77 kg (19.3 pounds)) and has since followed a solidly upward trend.

3) Fresh and frozen per capita consumption in Hawaii has ranged from 206 percent (in 1971) to 87 percent (in 1976) above the national average.

4) Canned per capita consumption in Hawaii since 1973 has been below the United States average.

5) Cured per capita consumption in Hawaii has been above the United States average for the period. Since this does not include local Hawaii production, the cured consumption rate in Hawaii is actually higher than the data indicate.

These results show that the most pronounced decline in the 1972-74 period occurred in the fresh and frozen category.

During this time, factors which may have possibly caused the decline were: a) a change in tastes due to the public concern over high mercury content in large pelagic fishes. Market observers during this period report that the local fishermen were unable to sell many of their fish and that it is conceivable it would have taken several years for the consumers to return to their higher preference levels for fish.

b) The observed reduction in the quantity of local supply during 1972-74 was possibly a result of a decline in demand due to a change in tastes. c) At the same time (1972) the visitor population began to grow much faster (12.2 percent annually) than the civilian resident population (2.1 percent annually). This visitor population may exhibit

differential consumption rates that are higher or lower than the resident population. However, any effect other than an absolute increase in the population is indeterminant. A diminished supply of fresh fish combined with a larger population base would result in a lower observed per capita consumption rate.

Hawaii has a large recreational fishery. The decline in the fresh category may be modified when consumption by recreationalists that is not reported in commercial catch is taken into consideration. Yearly data for recreational landings as a separate category are not available. A recent study¹ used Kailua-Kona, Hawaii, survey information to estimate game fish catch by commercial and recreational troller vessels for 1976. The authors' "Estimate I" (Table 4) represents an adjustment to statewide Division of Fish and Game data which accounts for underreporting and differential vessel catch rates by vessel category. When this estimate was considered, the total Hawaii supply of fish and fishery products (for 1976) increased from 17,829,909.1 kg (39,212,600 pounds) to 18,432,090.9 kg (40,550,600 pounds). Per capita consumption of fresh and frozen fish increased from 6.95 kg (15.3 pounds) to 7.32 kg (16.1 pounds). Total Hawaii per capita consumption increased from 9.27 kg (20.4 pounds) to 9.64 kg (21.2 pounds).²

otnote 1

otnote 2

Consumption of canned and cured fish are unaffected. It should be noted that the above estimate should therefore be considered as an approximation of one component of total recreational catch, that component caught by troller vessels and sold. Recreational catch that is not sold does not have to be reported.

Estimates of per capita consumption rates and the trends of these rates provide valuable input to research and policy planning. Specific determinants of this consumption have not been addressed here. However, these results have implications in particular for the Hawaii fishing industry, the aquaculture development program in Hawaii, the State of Hawaii Fisheries Development Plan and Regional Fishery Management Plans.

ACKNOWLEDGMENT

I wish to thank Michael F. Adams and Roy Mendelssohn of the Honolulu Laboratory, Southwest Fisheries Center, National Marine Fisheries Service and Girol Karacaoglu of Victoria University of Wellington for their comments and assistance. I especially wish to thank Ronald Sakamoto, U.S. Customs Import Specialist, Honolulu Customs District for patiently and frequently sharing his expertise during the research portion of this project.

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TEXT FOOTNOTES

1. Cooper, J. C., and M. F. Adams. 1978. Preliminary estimates of catch, sales, and revenue of game fish for the fishery conservation zone around the main Hawaiian Islands, by types of troll and longline vessels and by species, 1976. SWFC Admin. Rep. 24H, Natl. Mar. Fish. Serv., NOAA, Honolulu, HI 96812, 10 p. (Unpubl. rep.)
2. Population is total resident civilian.

Table 1.--Total Hawaii supply of commercial fish and shellfish
by source and year, 1970-77.¹

Year	Local commercial landings ²	Foreign imports ³	Interstate shipments ⁴	Total
<u>Thousand pounds</u>				
1970	11,282.2	22,960.3	5,896.0	40,138.6
1971	17,159.8	18,681.3	5,764.0	41,605.1
1972	14,754.7	28,953.6	4,682.0	48,390.3
1973	14,382.4	21,346.9	3,950.0	39,679.3
1974	11,323.7	24,467.2	4,068.0	39,858.9
1975	9,724.5	22,015.6	4,362.0	36,101.9
1976	15,272.3	19,846.3	4,094.0	39,212.6
1977	13,783.4	30,991.3	7,650.0	52,424.7

¹Based on the total supply of edible fishery products, without taking into consideration beginning or ending stocks, exports, or defense purchases.

²State of Hawaii, Department of Land and Natural Resources, Division of Fish and Game. Reports in round weight.

³U.S. Bureau of the Census (1970-77). Reported in net product weight.

⁴U.S. Army Corps of Engineers (1970-77). Reported in net product weight.

Table 2.--Per capita utilization of commercial fish and shellfish in Hawaii by year, source of fish, and two population groups, 1970-77.

Year	Resident civilian and military population					Resident civilian, military, and visitor population				
	Total resident civilian and military popula- tion, 1 July	Armed forces (1,000 persons) ¹	Total Hawaii supply (1,000 lb) ²	Per capita utilization		Total resident civilian and military plus visitor population ¹ (1,000 persons)	Visitors present (annual average) (1,000 persons)	Per capita utilization		Total
				Interstate shipments and foreign imports	Local commercial catch			Local commercial catch	Interstate shipments and foreign imports	
1970	775.8	53.2	40,138.6	37.2	14.5	803.4	37.6	14.1	35.9	50.0
1971	800.9	50.8	41,605.1	30.5	21.4	833.3	41.9	20.7	29.3	50.0
1972	823.3	52.0	48,390.3	40.9	17.9	865.9	51.3	17.0	38.9	55.9
1973	844.1	58.1	39,679.3	30.3	17.0	895.9	61.6	16.1	28.2	44.3
1974	855.4	57.5	39,858.9	33.4	13.2	913.6	66.0	12.4	31.2	43.6
1975	867.9	58.9	36,101.9	30.4	11.2	927.7	68.8	10.5	28.4	38.9
1976	883.5	57.8	39,212.6	27.1	17.3	952.7	78.5	16.0	25.2	41.2
1977	894.7	56.5	52,424.7	43.2	15.4	972.5	86.8	14.3	39.7	54.0

¹ [Hawaii.] Department of Planning and Economic Development (1978:6).

² Table 1, unadjusted for beginning and ending stocks, exports, or defense purchases. Excludes imports of nonedible fishery products.

Table 3.--United States and Hawaii total supply and per capita utilization of commercial fish and shellfish by year, 1970-77.

	<u>Total supply¹</u>		<u>Total per capita utilization²</u>	
	U.S.	Hawaii	U.S. ³	Hawaii
	<u>Million pounds</u>		<u>Pounds</u>	
1970	11,474	41.13	56.0	51.7
1971	11,804	43.11	57.0	51.9
1972	13,849	49.68	66.3	58.8
1973	10,378	40.94	49.3	47.3
1974	9,875	40.85	46.6	46.6
1975	10,129	36.95	47.4	41.6
1976	⁴ 11,555	40.55	53.7	44.4
1977	⁴ 10,579	53.63	48.8	58.6

¹Total supply for U.S. includes nonedible and industrial fishery products not included in total supply for Hawaii.

²Population is total resident civilian and military population present on 1 July.

³U.S. National Marine Fisheries Service (1978:70).

⁴Preliminary.

Table 4.--United States per capita consumption of commercial fish and shellfish by year and three types of preparation, 1970-77.¹

Year	Civilian resident population (million persons)	Per capita consumption			
		Fresh and frozen	Canned	Cured	Total
			<u>Pounds</u>		
1970	201.7	6.9	4.5	0.4	11.8
1971	204.3	6.7	4.3	0.5	11.5
1972	206.5	7.2	4.9	0.4	12.5
1973	208.1	7.5	5.0	0.4	12.9
1974	209.7	7.0	4.8	0.4	12.2
1975	211.4	7.4	4.3	0.4	12.1
1976	² 213.0	8.2	4.3	0.5	13.0
1977	² 214.7	7.8	4.6	0.4	12.8

¹U.S. National Marine Fisheries Service (1978:72).

²Preliminary.

Table 5.--Hawaii per capita consumption¹ of commercial fish and shellfish by year and three categories of preparation, 1970-77.

Year	Total civilian resident population 1 July (1,000 persons)	Per capita consumption			
		Fresh and frozen	Canned ²	Cured ³	Total
			<u>Pounds</u>		
1970	722.6	19.4	5.3	1.0	25.7
1971	750.1	20.5	4.6	0.7	25.8
1972	771.3	17.1	6.6	0.8	24.5
1973	785.9	16.7	3.8	0.9	21.4
1974	797.9	14.0	4.7	0.6	19.3
1975	809.0	15.3	3.6	0.7	19.6
1976	825.7	15.3	4.3	0.8	20.4
1977	838.3	17.8	4.0	0.9	22.7

¹Unadjusted for beginning and ending inventories and military purchases. Adjusted for exports to foreign countries from the Honolulu Customs district.

²Includes preserved and prepared which are canned but not included in cured.

³Does not include local production.

Table 6.--Hawaii per capita consumption of commercial fish and shellfish by year and three types of preparation, 1970-77 including annual average visitor population.¹

Year	Total civilian resident population plus visitors 1 July (1,000 persons)	Per capita consumption			
		Fresh and frozen	Canned ²	Cured ³	Total
			<u>Pounds</u>		
1970	760.2	18.9	5.0	0.9	24.8
1971	792.0	19.4	4.3	0.7	24.4
1972	822.6	16.0	6.2	0.7	23.0
1973	847.5	15.5	3.5	0.9	19.9
1974	863.9	12.9	4.4	0.9	18.2
1975	877.8	14.1	3.4	0.6	18.1
1976	904.2	14.0	3.9	0.7	18.6
1977	925.1	16.1	3.6	0.8	20.5

¹Unadjusted for beginning and ending inventories, and military purchases. Adjusted for exports from the Honolulu Customs district.

²Includes preserved and prepared which are canned but not included in cured.

³Does not include local production.

Table 7.--United States and Hawaii total per capita consumption of commercial fish and shellfish by year, 1970-77.¹

Year	<u>Total per capita consumption</u>	
	U.S.	Hawaii ²
	<u>Pounds</u>	
1970	11.8	25.7
1971	11.5	25.8
1972	12.5	24.5
1973	12.9	21.4
1974	12.2	19.3
1975	12.1	19.6
1976	³ 13.0	20.4
1977	³ 12.8	22.7

¹Population is total civilian resident population.

²Unadjusted for beginning and ending inventories and military purchases.

³Preliminary.

Table 8.--Foreign imports to Hawaii of fish and fish products for human consumption by year, type of preparation, quantity and Customs value,¹ 1970-77.

Year	Total			Fresh, chilled, frozen			Cured		Fish in airtight containers		Fish products (Pastes, balls, sticks, roe)		All shellfish	
	Quantity (1,000 lb)	Value (\$1,000)		Quantity (1,000 lb)	Value (\$1,000)		Quantity (1,000 lb)	Value (\$1,000)	Quantity (1,000 lb)	Value (\$1,000)	Quantity (1,000 lb)	Value (\$1,000)	Quantity (1,000 lb)	Value (\$1,000)
1970	22,906.3	10,354.8		19,417.9	6,376.9		81.1	78.4	422.1	215.5	481.7	374.8	2,557.5	3,309.2
1971	18,681.2	10,633.1		13,893.0	5,146.2		85.0	86.8	974.3	397.7	810.0	479.1	2,919.0	4,523.3
1972	28,953.6	15,755.6		23,693.8	9,816.9		85.8	147.0	1,317.9	497.3	1,123.5	609.3	2,732.8	4,685.1
1973	21,346.9	13,633.5		16,496.5	7,703.3		119.5	212.9	853.3	381.4	1,222.8	878.9	2,654.9	4,457.0
1974	24,467.2	17,303.3		19,340.0	10,182.8		113.4	145.3	767.5	501.6	1,342.7	854.2	2,903.6	5,619.4
1975	22,015.6	13,393.4		17,320.0	7,815.2		87.0	119.9	816.1	433.1	1,583.2	1,114.0	2,208.8	3,911.1
1976	19,846.3	14,185.4		14,917.3	7,380.1		131.0	163.3	877.3	500.5	1,634.0	1,118.4	2,286.7	5,023.1
1977	30,991.3	22,875.4		26,448.9	15,729.3		94.8	152.6	746.2	521.2	1,387.4	1,151.2	2,314.0	5,321.1

¹Customs value generally represents a value in the foreign country, and therefore excludes U.S. import duties, freight, insurance, and other charges incurred in bringing the merchandise to the United States. This value may not reflect the actual transaction value. These values are unadjusted.

Table 9.--Imports of fresh, frozen, chilled fish, and shellfish by major countries of origin,¹ quantity, and Customs value,² 1976 and 1977.

Country of origin	Quantity (1,000 lb)	Customs value (\$1,000)	Quantity (1,000 lb)	Customs value (\$1,000)
	<u>1976</u>		<u>1977</u>	
<u>Fish</u>				
New Hebrides	6,016.9	3,216.3	19,014.7	11,991.0
Philippines	23.6	19.5	3,345.9	865.4
Taiwan	1,876.1	1,411.3	2,749.4	2,019.6
Japan	1,070.7	742.1	727.2	534.2
Panama	3,856.0	1,104.0	185.5	55.7
Fiji	1,180.0	538.7	--	--
<u>Shellfish</u>				
New Zealand	248.1	1,407.9	213.0	1,514.0
Taiwan	134.7	457.5	93.6	369.0
Japan	42.3	129.3	18.6	61.4

¹Country of origin as determined by U.S. Customs.

²See footnote 1, Table 8.

Table 10.--Foreign imports to Hawaii of fishery items, canned and in airtight containers, all manner of preparation, net weight in thousand pounds, 1970-77.

Year	Salmon	Sardines	Tuna	Anchovies	Shellfish	Other	Total
<u>Thousand pounds</u>							
1970	18.6	45.0	95.0	54.6	1,323.6	208.9	1,745.7
1971	45.9	182.5	85.6	153.3	1,218.7	507.0	2,193.0
1972	68.2	389.5	55.2	228.4	1,247.0	576.6	2,564.0
1973	¹ --	26.9	78.7	242.1	1,225.5	506.0	2,078.8
1974	11.6	21.8	120.0	213.1	1,898.8	401.0	2,666.3
1975	¹ --	6.5	112.1	358.5	1,315.9	339.0	2,131.9
1976	¹ --	34.3	139.3	355.7	1,319.8	348.0	2,197.1
1977	11.6	44.2	29.6	305.3	1,243.4	355.5	1,989.6

¹None reported.

Table 11.—Foreign imports to Hawaii, by principal items, 1976 and 1977.

Item	1976		1977	
	<u>Thousand pounds</u>	<u>Thousand dollars¹</u>	<u>Thousand pounds</u>	<u>Thousand dollars¹</u>
Edible fishery products				
<u>Fresh and frozen:</u>				
Tuna				
Albacore	5,177.6	2,980.8	14,959.8	10,183.9
Skipjack	2,200.2	627.5	2,343.7	598.7
Yellowfin	4,136.3	1,507.9	5,287.8	2,158.9
Filletts	2,494.1	1,832.1	3,253.1	2,358.4
Shellfish				
Clams	29.2	27.7	17.3	26.6
Lobsters	297.6	1,619.8	245.4	1,654.9
Shrimp and prawns	242.9	779.2	137.5	486.9
Other	948.6	551.5	637.4	576.2
<u>Canned</u>				
Salmon	0	0	11.6	22.6
Anchovies	355.7	94.0	305.3	94.4
Sardine				
Not in oil	23.9	8.0	43.7	25.3
Tuna	139.3	128.3	29.6	35.2
Bonito and yellowtail	3.1	7.5	2.2	6.1
Clams	182.1	234.0	174.8	275.7
Shrimp	31.4	57.9	50.5	104.9
Other	510.0	549.5	474.4	768.4

Table 11.--Continued.

Item	1976		1977	
	<u>Thousand pounds</u>	<u>Thousand dollars¹</u>	<u>Thousand pounds</u>	<u>Thousand dollars¹</u>
<u>Cured</u>				
Pickled, salted, or dried	577.8	1,078.5	719.2	1,278.6
Smoked or kippered	81.3	80.5	57.1	80.4
<u>Other fish and shellfish</u>	2,415.2	2,020.6	2,240.8	2,139.1
Total edible fishery products	19,846.3	14,185.4	30,991.3	22,875.2

¹See footnote 1, Table 8.

Table 12.—Estimated Hawaii per capita consumption of foreign imports of fish, fishery products, and shellfish by year and type of preparation, 1970-77.¹

Year	Total civilian resident population, July 1 (1,000 persons)	Per capita consumption					Shellfish Total
		Fresh, chilled, frozen ²	Dried, salted pickled, smoked, kippered	Fish in airtight containers	Pastes, balls, sticks		
1970	722.6	6.2	0.1	0.6	0.7	0.5	8.1
1971	750.1	4.8	0.1	1.3	1.1	0.7	8.0
1972	771.3	5.5	0.1	1.7	1.5	0.7	9.5
1973	785.9	5.0	0.2	1.1	1.6	0.5	8.4
1974	797.9	3.4	0.1	1.0	1.7	0.4	6.6
1975	809.0	4.7	0.1	1.0	2.0	0.4	8.2
1976	825.7	3.8	0.2	1.1	2.0	0.4	7.5
1977	838.3	2.0	0.1	0.9	1.7	0.3	5.0

¹Unadjusted for exports, defense purchases, or beginning or ending stocks.

²Based on imported weight which is net product weight. In some cases this is meat-weight; in others, this is whole or round weight. Customs reports only net product weight.

ASSESSMENT OF THE SOUTH PACIFIC ALBACORE STOCK

Jerry A. Wetherall
Fletcher V. Riggs
Marian Y. Y. Yong

Southwest Fisheries Center
National Marine Fisheries Service, NOAA
Honolulu, Hawaii 96812

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INTRODUCTION

The albacore, Thunnus alalunga, has been a principal target of tuna fishing in the South Pacific since Japanese longliners began operating near the Solomon Islands in 1952. The Japanese fleet extended eastward and in 1954 some of these vessels began landing albacore, yellowfin tuna, T. albacares, and bigeye tuna, T. obesus, at Pago Pago, American Samoa, under contract to a U.S. cannery there. The fishery grew steadily and was entered by longliners from Taiwan and the Republic of Korea,

based at Pago Pago (Table 1). A second U.S. cannery was opened in American Samoa, and other bases for foreign tuna longliners were established in the New Hebrides, Fiji, and Tahiti. Whereas most of the South Pacific albacore catch made by longliners of Korea and Taiwan is taken by vessels based at American Samoa and other foreign ports, the majority of the Japanese catch has always been by Japan-based longliners, and the Japanese eventually withdrew from the Pago Pago base in 1973.

The longline fishery for albacore is carried out over a wide area from about long. 150°E to 120°W and from equatorial waters south to lat. 40°S (Figure 1). Until the 1970's effort was exerted mostly north of lat. 20°S, especially during the first and fourth quarters, but there

has been an increase in effort southward in recent years (Table 8).

While albacore remain the principal target of longliners based at Pago Pago, yellowfin and bigeye tunas make up a substantial fraction of the

landings, especially by Korean vessels since 1971 (Table 2). All of these historical developments are discussed in greater detail by Otsu (1966), Otsu and Sumida (1968), Skillman (1975), and Yoshida (1975).

Since the buildup of fishing effort in the South Pacific during the 1960's, there has been a keen interest among government scientists and the fishing industry in assessing the albacore resource and measuring the effects of fishing on the stock. The first comprehensive assessment was made by Skillman (1975). He estimated total catches, constructed a first-cut abundance index based on the catch per unit effort (CPUE) of American Samoan-based vessels and fit a production model. He concluded the stock was fully harvested, given the prevailing fishing practices, but left open the possibility that yield could be increased by altering the age-specific patterns of fishing mortality.

In this paper we re-evaluate the status of the South Pacific albacore stock, using more complete and reliable catch statistics than were available to Skillman. We construct an improved abundance index and repeat the production model analysis. Finally we briefly examine the prospects of increasing harvests by altering age at first capture. This is done with an age-structured simulation model of the albacore stock.

Catch Statistics

Estimates of the catch of South Pacific albacore by Japanese longliners are available from the beginning of fishing in 1952. Sample logbook statistics are used to estimate the total catch in number of fish. Estimates of the average weight per fish are obtained by sampling the landings. These two factors are multiplied and summed over time-area strata to produce total yield figures for each year. Tonnage estimates used in this paper were provided by S. Ueyanagi of the Far Seas Fisheries Research Laboratory, Shimizu, Japan.

The catch statistics for longliners from Taiwan are compiled in a similar fashion and have been published annually since 1967. Catch data for earlier years, 1963 through 1966, were provided for this analysis by R. T. Yang of National Taiwan University. Until 1978 the Taiwan government did not determine the size composition of tuna catches, and average weight figures used in the official Taiwan statistics are based on "eye ball" assessments of weight made as the longlines are hauled. For this reason, we constructed our own estimates of total tonnage. We multiplied the published catch in numbers in each 5° square-month stratum by average weights of albacore caught by vessels from Taiwan in that stratum and measured by biological technicians at the landing sites in Pago Pago.

In the case of Korea the only government statistics available to us were the published longline data covering 1966-70, giving sample catch in number of fish and associated nominal effort. We did not use these statistics. Instead, we estimated the annual Korean albacore catches as the product of two factors: a) the sum of the South Pacific albacore catch by longliners of Japan and Taiwan (as estimated above), and b) the estimated ratio of Korean catches to the combined catches of Japan and Taiwan, as derived from the statistics of Skillman (1975).

The estimated total catches of South Pacific albacore by Japan, Taiwan, and Korea are given in Table 3. The catch by other nations includes small quantities landed by longliners in Fiji and by trollers in Chile and New Zealand.

The catch statistics presented above for Japan and Taiwan are based on the sampling of vessel logbooks (Korea has a similar system). Besides these data sources, there has been since 1962 a separate system of logbook statistics for those vessels based at American Samoa. Data on the numbers of hooks fished and resulting catch by species (number of fish) for each day of fishing, along with fishing positions, are obtained from 80%-90% of the vessels. These statistics are collected by the Office of Marine Resources in Pago Pago, and copies are processed by the NMFS Honolulu Laboratory. In addition, NMFS maintains files of landings statistics from the Starkist and Van Camp tuna canneries in Pago Pago. These give the tonnage of tunas and other species landed by the longliners, number of trips, trip length, and other data. Tables 2 and 4 present some of these statistics.

Table 4

Trends in Catch and Nominal Effort

Table 3 shows that the total albacore catch rose to high levels in the first decade of the fishery and has fluctuated around an average annual catch of about 36,000 metric tons (MT) since 1962. The catch peaked in 1973 when 49,000 MT were taken. Trends in nominal effort are best indicated by the data in Table 4, which show the growth in the total number of trips and days fished per trip for vessels based at Pago Pago. Total days fished reached a peak in 1973 and then dropped sharply after the fuel crisis forced the withdrawal or inactivity of many longliners beginning in mid-1974.

Size Composition

Information on the size composition of South Pacific albacore catches is available from two sources. The Japanese have sampled their catches and determined fork-length distributions since the 1950's. On a much larger scale, NMFS established a biological sampling program at Pago Pago in 1962, and gathered data on sex, fork length, and weight of albacore landed by vessels of Japan, Korea, and Taiwan. The time and position of capture were estimated for each sample. Since 1970 sex and weight determinations have been discontinued due to changes in unloading procedures at the canneries, but length-frequency data are still gathered.

In this report we discuss only the NMFS data. This has been treated extensively by Otsu and Sumida (1968) and Yoshida (1975). The size composition of South Pacific albacore varies markedly between latitudes and sex (Figures 2 and 3). Variation between longitudes and seasons is not so significant. Table 5 shows mean weights and fork lengths of males and females in 5° bands of latitude from the equator to lat. 45°S. North of lat. 30°S males are consistently larger than females and the difference is especially pronounced at the mid-latitudes of lat. 15°-25°S where the mean size of both sexes is greatest. In both sexes, average size increases going southward from the equator until about lat. 25°S, and then declines sharply further south.

The size composition of catches also varies with latitude. Figure 3, with sexes combined, shows that the catch north of lat. 25°S is composed almost entirely of fish larger than 80 cm, and that the fork length distributions are unimodal. Figure 4, taken from Yoshida (1975),

gives latitudinal distributions of fork length separated by sex, and shows this even more clearly. The variability within these unimodal distributions is wholly consistent with the expected variation of size at age for a single cohort as predicted by stochastic versions of the von Bertalanffy growth model, particularly if we assume South Pacific albacore grow to the same maximum sizes as their North Pacific counterparts. The proportion of very large albacore (>110 cm fork length) in South Pacific catches seems to be somewhat less than in the North Pacific, but this may be due to differences in availability.

South of lat. 25°S the size composition of albacore catches changes dramatically, with progressively smaller fish appearing in samples along with the large ones found further north. Either these younger albacore (less than about 5 years) are virtually absent north of lat. 25°S or they are simply unavailable to the longline gear in this region.

In the jig fishery for South Pacific albacore off New Zealand fish range from 45 to 100 cm with 2-4 year old fish predominating (Habib and Cade 1978). Off of Chile, the small catch by trollers consists of fish over a similar size range, with 4-year olds appearing most frequently (Yoshida and Otsu 1963).

Fig. 5
Tables 6,7

Figure 5 and Tables 6 and 7 show the changes in size composition and mean size in the catches since 1962. [All the composite frequency distributions are weighted by total catches in the substrata.] There was no significant change in size composition until the late 1960's, when expansion of effort south of lat. 20°S (Table 8) brought more smaller fish into the catch. In 1973 and 1974 there was a dramatic

Table 8

shift towards smaller albacore in the catch, but the larger fish prevailed again in 1975 and 1976 (Figure 5).

Index of Abundance

We constructed an annual index of abundance for albacore within a specified stock index region based on an average of standardized indices for each group of longliners based at American Samoa. The index for each class (nationality) of vessels was computed from

$$U_i = \frac{\sum_{k=1}^{\ell_i} \sum_{j=1}^{m_{ik}} \frac{C_{ijk} A_{ijk}}{f_{ijk} p_{ijk}}}{\sum_{k=1}^{\ell_i} m_{ik}}$$

where U_i = index of abundance in year i in the defined index region

C_{ijk} = catch in the j^{th} fishing zone and k^{th} fishing season during year i

f_{ijk} = associated nominal effort (number of hooks)

A_{ijk} = area of the j^{th} fishing zone relative to a standard zone

p_{ijk} = ratio of the average abundance of albacore in the $(j, k)^{\text{th}}$ cell during year i to the average abundance in the entire index region during year i

ℓ_i = actual number of seasons in which fishing occurred in year i

m_{ik} = actual number of fishing zones in which effort was exerted during the k^{th} fishing season of year i

All elements of U_i are observed except for p_{ijk} . Let n_i denote the total number of fishing zones in the stock region and r_i be the total number of potential fishing seasons. Then for years when the time-space coverage of the index area by the fleet is complete, $\ell_i = r_i$ and $m_{ik} = n_i$ for all i and k and

$$\hat{p}_{ijk} = \frac{\left(\frac{C_{ijk} A_{ijk}}{f_{ijk}} \right)}{\sum_{k=1}^{\ell_i} \left(\frac{m_{ik} C_{ijk} A_{ijk}}{\sum_{j=1}^{\ell_i} \frac{C_{ijk} A_{ijk}}{f_{ijk}}} \right) n_i} \bigg/ m_{ik} \cdot \ell_i$$

In this event U_i reduces to the ordinary average-of-ratios catch per unit effort statistic, except that the differences in area of fishing zones are taken into account. Of course, when $\ell_i < r_i$ and/or $m_{ik} < n_i$ for some i , then $\hat{p}_{ijk}$ will be biased unless the population is distributed uniformly in time and space or fishing zones and seasons are chosen at random. These conditions are unlikely at best. To circumvent these difficulties Honma (1974) invokes the assumption that the temporal and spatial distribution of the stock in the index region is constant each year, i.e., $p_{ijk} = p_{jk}$ for all i , and suggests estimating the p_{jk} 's using data from "standard" years when coverage was relatively complete. Supposing there are a_{jk} standard years when the $(jk)^{th}$ stratum was fished, we estimated the average p_{jk} for that stratum by

$$\hat{p}_{jk} = \frac{\sum_{i=1}^{a_{jk}} \hat{p}_{ijk}}{a_{jk}}$$

where $\hat{p}_{ijk}$ is as given above.

In applying this procedure to South Pacific albacore we used the logbook data for American Samoa-based longliners from Japan, Korea, and Taiwan. The boundaries of the stock index area were set at lat. 0° to 35°S and long. 160°E to 115°W (Figure 1). Fishing seasons and zones were defined as quarters of the year and areas of 5° lat. $\times$ 5° long.

Before the p_{jk} 's and the abundance indices were computed, the catches in each stratum were converted from numbers of albacore to weight of albacore by applying detailed average weight statistics derived from the Pago Pago sampling. Separate average weight estimates were usually available by nation, year, quarter, latitude (5° bands) and longitude (10° bands). In cases where corresponding average weight data were not available for a catch in a given stratum, an average figure for the appropriate latitude was substituted.

Estimates of the p_{jk} 's were computed using the nominal effort and catch-in-weight statistics of both Taiwan and Korea over the standard years 1967 through 1977, when relatively full coverage of the index region was achieved. In each case, p_{jk} were estimated only for strata fished at least five times during the period of standard years (i.e., $a_{jk} \geq 5$). Further, only those cells with $a_{jk} \geq 5$ were included in the subsequent estimation of the stock abundance indices.

Abundance indices, based on p_{jk} estimates from Taiwan data, were computed for Japan, Taiwan, and Korea. (Indices using Korean p_{jk} 's were not substantially different.) The indices for Taiwan and Korea were then standardized to the Japanese index following a fishing power analysis (Table 9). The fishing power analysis employed indices over the 1966-72 period.

Table 10
Fig. 6

After the standardization, indices for each nationality were averaged into a single index. This index is given in Table 10 and Figure 6. The index has been scaled to the Japanese catch rates for 1962 in kg/100 hooks. Figure 6 also shows an index of abundance based on published and unpublished Japanese longline data from 1952 through 1976, using the same p_{jk} as with the American Samoa data. This index is based on Japan-based as well as the Pago Pago-based vessels (Japanese vessels were absent from American Samoa beginning with 1973), and was standardized to the composite American Samoa index. Both the composite index based on American Samoa logbook data and this Japanese index show an apparent decline in abundance since the early 1960's. But the index derived from the unpublished Japanese statistics does not conform to our expectations during the first decade of the fishery when catch rose from nothing to nearly 40,000 MT. Whether this reflects inadequacies in the indexing procedure, biases in the basic data or oversimplified expectations remains to be determined. For the purposes of our production model analysis we will assume the composite index from 1962 to 1977 truly reflects a decline in average abundance over this period.

Estimating Effective Effort

The total effective effort on South Pacific albacore was estimated each year from 1962 to 1977 by dividing the composite index of abundance into the estimated total catch. Results are given in Table 10 and plotted in Figure 6, with units standardized in terms of effort by Japanese vessels based at Pago Pago in 1972.

Production Model

A production model was fit to the total catch statistics and effective effort measure (Table 10) using Fox's PROFIT program (Fox 1975). Equilibrium conditions were approximated by smoothing the effective effort over 1-, 2-, 3-, or 4-year periods. The model's shape parameter, m , was both fixed at 2.0 (Schaefer form) and allowed to vary as one of the estimated parameters. Results are given in Table 11. It is clear from Figure 7 that the Schaefer model would be inappropriate. The remaining results, for m variable, indicate an MSY between 33,000 and 36,000 MT. The predicted optimum effective effort levels range from 60×10^6 hooks to 389×10^6 hooks, or 2.2 to 14.4 times the 1962 effort and 0.31 to 2.0 times the 1977 effective effort. The low (E_{opt}/E_{77}) figure of 0.31 is based on a 1-year smoothing, so is perhaps less reasonable than the other cases. Still, with both 2- and 4-year effort averaging, the analysis predicts that optimum effort would require a cutback of nearly 40% from the 1977 level. Figure 8 shows the equilibrium yield-effort curve for the 3-year averaging, and Figure 9 gives the result for 2-year smoothing. Both yield curves are fairly flat over a broad range of effort and predict similar catches for effort levels in the neighborhood of recently experienced ones. According to these production models, virtually no increase in yield can be expected to accompany an expansion of effort above the 1977 level, and in fact an average yield nearly equal to the MSY could be achieved at half the 1977 effort.

In 1975 Skillman presented a production model for South Pacific albacore, based on unadjusted ratio-of-average catch per hook statistics of Japanese longliners based at Pago Pago and on total catch statistics from the Asian Tuna Conference proceedings and other sources. His best estimate of MSY was about 35,000 MT at an effort roughly 4.5 times the 1962 effort. The variability in Skillman's data also left some doubt as to the shape of the production curve at high effort levels.

Effects of Age at First Capture on MSY Under Different Stock-Recruitment Models

In our production model results there is some suggestion that recruitment to the South Pacific albacore stock may be fairly independent of the spawning stock size. We estimated this constant recruitment level by applying the approach of Suda (1970) to the estimated annual total catch in number of fish and the associated effective effort statistics, again smoothed over 3-year periods to approximate equilibrium conditions. Using a nonlinear regression procedure, we fitted the model

$$\ln(C_1/f_1) = \ln(qR) - \ln(M + q f_1)$$

where C_1 = annual catch in number of albacore

f_1 = associated effective effort (smoothed)

q = catchability coefficient

R = number of fish recruited to exploited stock

M = natural mortality rate

In this model, the same estimate of R results for all guesses of M ; and estimates of q are directly proportional to the M value. We fixed M at 0.4, and the resulting estimates of R and q were 2.54×10^6 fish and 1.875×10^{-8} /hook. The fitted model is shown in Figure 10. Assuming the recruitment estimate corresponds to fish at about 5 years of age (85 cm fork length), the estimated number of recruits at an age of 2 years is 8.43×10^6 fish.

An age-structured simulation model was constructed to study the response of maximum sustainable yield of the albacore stock to changes in age at first capture under a variety of stock-recruitment hypotheses. Knife-edge recruitment was assumed. The natural mortality rate was assumed constant at 0.4 year^{-1} . An age-length model for North Pacific albacore was used in the absence of such a model for the South Pacific stock ($L(t) = 135.6 (1 - \exp(-0.17(t+0.87)))$), where L is fork length and t is age in years. Parameters of the length-weight relationship were estimated from Pago Pago sample statistics; the resulting equation was $W = 1.681 \times 10^{-5} \times L^{3.059}$, where weight is in kilograms and fork length is in centimeters.

The stock-recruitment hypotheses displayed in Figure 11 were studied. The equation of this model is

$$R = R_{\max} \left(\frac{S}{S_{\max}} \right)^{\beta}$$

where $R_{\max}$ and $S_{\max}$ are upper limits on recruitment (R) and spawning biomass (S). We set $R_{\max} = 8.43 \times 10^6$ fish so that with $\beta = 0$,

$R = 8.43 \times 10^6$ fish (constant). $S_{\max}$ was determined as the biomass of spawning stock in the absence of fishing when $R = R_{\max}$. Assuming fish above 5 years old are members of the spawning stock, $S_{\max} = 1.33 \times 10^5$ MT.

With this set of parameters the maximum sustainable yield was determined for combinations of $\beta(0, 0.15, 0.32, 0.51)$ and age at first capture (2 years, 3 years, 4 years, 5 years, 6 years, 7 years). Results are given in Figure 12. Under the constant recruitment hypothesis, the simulation model computes a maximum sustainable yield of 37,800 MT, corresponding to an age at first capture of 4 years. However, only slight increase in potential yield would result from lowering age at first capture from 5 years to 4 years. Under the more conservative stock-recruitment hypotheses, the yield potentials are reduced substantially and maximum sustainable yield is achieved at progressively higher ages at first capture. We also ran the model with $M = 0.2$ and with appropriately adjusted $S_{\max}$ and $R_{\max}$. In this case the dome in the constant-recruitment yield curve disappeared and MSY was an increasing function of age at first capture (over the range of 2-6 years) for all stock recruitment hypotheses.

Future Studies

The production model analysis is intended to give no more than a rough idea of the status of the South Pacific albacore stock. As a guide for fishery management policy the analysis suggests that expansion of nominal longline effort should not be encouraged (as far as albacore

catches are concerned), and in fact that substantial economic benefits might result from a cutback of effort. It would be interesting and useful to study the economics of the fleets based at Pago Pago, and to try to forecast the expected effort levels under a variety of economic conditions.

On the biological side, there are several tasks needing attention. First, there is an abundance of size composition data, so the possibility of doing a cohort analysis should be explored. A cohort analysis is likely to be difficult because relatively few age groups are found in the catch and there is no clear separation of length frequency modes for most of the catch. If a cohort analysis is attempted, it should be done by sex, and sex composition will have to be estimated for catches since 1970.

- The simulation model studies could be expanded, exploring more complicated hypotheses with respect to age-specific rates of natural mortality and catchability. An investigation of the robustness of the production model could be part of this.

- A detailed study of relative population density by time and area should be completed. Indices of abundance by size-class should be constructed, and forecasting models using such indices should be attempted.

- The possibility of tagging 2- and 3-year old albacore in New Zealand waters should be evaluated, so that hypotheses on the interdependence of the surface and longline fishery can be tested and so that growth rates and migration patterns can be estimated.

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Table 1.--Number of longline vessels based at Pago Pago, American Samoa, by nationality, 1954-76.

Year	Number of vessels				Total
	Japan	Taiwan	Korea	Undetermined	
1954	17	--	--	1	18
1955	50	--	--	--	50
1956	56	--	--	--	56
1957	61	--	--	1	62
1958	76	--	2	1	79
1959	64	--	4	1	69
1960	60	--	3	1	64
1961	55	--	2	1	58
1962	79	--	5	1	85
1963	117	--	10	1	128
1964	94	11	16	--	121
1965	101	23	33	--	157
1966	79	76	55	--	210
1967	62	128	69	--	259
1968	39	110	85	--	234
1969	18	71	76	--	165
1970	9	115	81	--	205
1971	4	124	90	--	218
1972	2	135	95	--	232
1973	--	172	172	--	344
1974	--	149	171	--	320
1975	--	77	135	--	212
1976	--	93	119	--	212

Table 2.--Landings of albacore (round weight, kg) and yellowfin and bigeye tunas (gilled and gutted, kg) at American Samoa by longliners from Japan, Korea, and Taiwan.

Year	Nation	Albacore	Yellowfin tuna	Bigeye tuna
1954	Japan	349,147	602,546	26,556
	Korea	--	--	--
	Taiwan	--	--	--
1955	Japan	2,109,792	2,260,164	24,181
	Korea	--	--	--
	Taiwan	--	--	--
1956	Japan	3,706,218	2,107,167	215,694
	Korea	--	--	--
	Taiwan	--	--	--
1957	Japan	6,003,530	1,577,288	310,425
	Korea	--	--	--
	Taiwan	--	--	--
1958	Japan	9,784,216	2,412,130	455,112
	Korea	145,974	70,338	17,818
	Taiwan	--	--	--
1959	Japan	9,814,443	1,705,524	422,299
	Korea	456,427	67,350	24,396
	Taiwan	--	--	--
1960	Japan	10,581,094	1,046,692	196,497
	Korea	609,897	81,976	49,567
	Taiwan	--	--	--
1961	Japan	9,225,419	1,230,710	131,197
	Korea	330,047	46,311	9,100
	Taiwan	--	--	--
1962	Japan	12,605,012	1,348,594	518,110
	Korea	634,535	46,658	26,104
	Taiwan	--	--	--
1963	Japan	12,669,394	1,819,131	1,310,142
	Korea	1,460,533	251,672	241,966
	Taiwan	--	--	--
1964	Japan	8,064,088	1,869,650	1,137,607
	Korea	1,767,730	400,476	158,912
	Taiwan	556,279	110,510	48,093
1965	Japan	9,506,437	2,398,729	1,269,411
	Korea	4,344,663	1,429,556	1,302,985
	Taiwan	1,607,648	647,633	360,810
1966	Japan	8,898,816	2,407,009	1,339,728
	Korea	9,116,649	2,019,914	2,268,187
	Taiwan	7,472,107	2,114,768	918,053
1967	Japan	7,477,506	1,124,017	994,319
	Korea	9,699,115	2,070,612	2,699,328
	Taiwan	11,133,742	2,131,791	1,846,787
1968	Japan	3,155,537	1,052,467	274,966
	Korea	6,176,349	3,045,761	1,273,197
	Taiwan	8,090,622	3,238,997	1,221,084
1969	Japan	1,570,750	649,830	80,584
	Korea	10,181,956	4,912,826	1,812,130
	Taiwan	6,977,831	2,576,833	1,327,978
1970	Japan	956,631	225,756	6,242
	Korea	11,942,262	3,663,516	1,321,666
	Taiwan	10,981,609	3,808,017	1,646,830
1971	Japan	379,523	75,240	84
	Korea	9,952,463	4,647,388	945,882
	Taiwan	11,861,105	3,844,595	1,112,017
1972	Japan	59,710	54,832	--
	Korea	9,854,751	6,685,235	1,138,297
	Taiwan	10,253,178	6,036,794	2,001,947
1973	Japan	--	--	--
	Korea	16,764,572	6,660,751	2,527,801
	Taiwan	13,383,806	3,819,636	1,968,300
1974	Japan	--	--	--
	Korea	6,837,493	5,193,551	2,138,182
	Taiwan	7,803,417	2,084,428	1,266,750
1975	Japan	--	--	--
	Korea	4,360,973	4,604,442	1,545,420
	Taiwan	3,478,611	1,537,972	803,607
1976	Japan	--	--	--
	Korea	8,509,220	4,885,548	2,953,224
	Taiwan	6,044,421	1,248,680	562,569

Table 3.--Estimated total catches of South Pacific albacore, 1952-77.

Column	1	2	3	4	5	6	7
Year	Japan	Taiwan	Japan and Taiwan	R	Korea	Other	Total
1952	210	--	210	--	--	--	210
1953	1,091	--	1,091	--	--	--	1,091
1954	10,200	--	10,200	--	--	--	10,200
1955	8,420	--	8,420	--	--	--	8,420
1956	6,220	--	6,220	--	--	--	6,220
1957	9,764	--	9,764	--	--	--	9,764
1958	21,558	--	21,558	--	146	--	21,704
1959	19,344	--	19,344	--	456	--	19,800
1960	23,756	--	23,756	--	610	--	24,366
1961	25,628	--	25,628	--	330	--	25,958
1962	38,880	0	38,880	0.0154	599	--	39,479
1963	33,500	608	34,108	0.0400	1,367	--	35,475
1964	21,435	629	22,064	0.1319	2,911	--	24,975
1965	19,305	1,640	20,945	0.3058	6,405	100	27,450
1966	23,401	6,669	30,070	0.3597	10,817	500	41,387
1967	16,640	14,910	31,550	0.4347	13,717	105	45,372
1968	7,707	14,496	22,203	0.4566	10,138	14	32,355
1969	5,559	9,883	15,442	0.6451	9,963	--	25,405
1970	6,560	12,463	19,023	0.6097	11,599	50	30,672
1971	4,339	21,584	25,923	0.5586	14,482	200	40,605
1972	2,796	23,050	25,846	0.5586	14,439	468	40,753
1973	2,381	28,858	31,239	0.5586	17,452	584	49,275
1974	1,847	19,980	21,827	0.5586	12,194	890	34,911
1975	1,045	15,092	16,137	0.5586	9,015	1,827	26,979
1976	1,906	19,954	21,860	0.5586	12,212	2,462	36,534
1977	2,240	21,345	23,585	0.5586	13,176	4,610	41,371

Comments:

Column 1 - Japanese longline catch in metric tons, courtesy of S. Ueyanagi, Far Seas Fisheries Research Laboratory.

Column 2 - Catch by Taiwan's high-seas longliners (>50 GT) based at foreign ports, estimated from published Taiwan catch statistics and average weights of albacore landed at Pago Pago.

Column 3 - Column 1 plus column 2

Column 4 - R is ratio of Korean catch of South Pacific albacore to total catch of this species by Japan and Taiwan, estimated from data in Skillman (1975).

Column 5 - Column 3 x column 4, except for 1958-61, which are from American Samoa cannery records.

Column 6 - Includes catch by Chile (from FAO statistics), Fiji (courtesy of Ian Brown), and New Zealand (from Habib and Cade 1978).

Table 4.--Estimated number of vessel trips, fishing days per trip, and total fishing days for longliners based at American Samoa, 1954-76.

	Japan			Taiwan			Korea		
	Days/trip	Trips	Days	Days/trip	Trips	Days	Days/trip	Trips	Days
1954	--	58	--	--	--	--	--	--	--
1955	--	142	--	--	--	--	--	--	--
1956	--	262	--	--	--	--	--	--	--
1957	17.4	263	4,576	--	--	--	--	--	--
1958	21.1	330	6,963	--	--	--	22.6	7	158
1959	24.4	287	7,003	--	--	--	26.7	14	374
1960	23.3	283	6,594	--	--	--	23.0	44	1,012
1961	21.5	260	5,590	--	--	--	25.0	8	200
1962	22.0	349	7,678	--	--	--	24.9	40	996
1963	24.6	423	10,406	--	--	--	30.9	69	2,132
1964	27.5	277	7,618	23.2	27	626	27.4	69	1,891
1965	30.7	275	8,442	27.6	97	2,677	34.2	165	5,643
1966	32.1	229	7,351	27.5	295	8,112	41.6	246	10,234
1967	35.7	202	7,211	33.0	355	11,715	44.3	241	10,676
1968	39.6	100	3,960	40.3	267	10,760	47.5	214	10,165
1969	38.7	47	1,819	38.9	213	8,286	47.3	289	13,670
1970	37.9	26	985	40.4	326	13,170	46.7	289	13,496
1971	40.2	13	523	45.3	328	14,858	54.5	282	15,369
1972	29.8	4	119	46.8	350	16,128	54.4	349	18,986
1973	--	--	--	52.2	422	22,028	56.6	479	27,111
1974	--	--	--	55.4	327	18,116	47.6	422	20,087
1975	--	--	--	62.5	134	8,375	55.8	262	14,620
1976	--	--	--	59.2	152	8,998	57.6	276	15,898

Table 5.--Mean fork length (top row, cm) and weight (bottom row, kg) of harvested South Pacific albacore by latitude, sex, and vessel nationality.

	Latitude										
	0°-5°S	5°-10°S	10°-15°S	15°-20°S	20°-25°S	25°-30°S	30°-35°S	35°-40°S	40°-45°S	0°-45°S	
Sex:											
Male	88.8 15.5	90.9 16.6	93.9 18.4	97.3 20.5	97.2 20.6	87.6 15.3	83.3 13.1	77.6 10.4	-- --	91.2 17.0	
Female	86.8 14.4	87.6 14.8	89.8 16.0	92.4 17.5	91.7 17.2	86.6 14.5	84.1 13.3	78.8 10.9	-- --	88.0 15.1	
Undeter- mined	90.6 16.5	90.6 16.6	93.3 18.1	95.4 19.4	95.3 19.4	88.7 15.8	81.9 12.6	81.0 12.1	77.9 10.6	88.2 15.6	
Nation:											
Japan	88.0 15.1	90.6 16.5	93.4 18.1	96.7 20.1	95.6 19.6	87.7 15.3	83.7 13.3	75.0 9.6	-- --	-- --	
Taiwan	87.9 15.0	89.6 15.9	92.6 17.7	95.1 19.2	95.4 19.4	88.6 15.7	82.3 12.7	81.7 12.5	85.6 14.8	-- --	
Korea	89.2 15.7	90.0 16.1	92.5 17.6	95.3 19.3	95.1 19.3	87.3 15.1	82.7 12.9	80.7 12.0	77.9 10.6	-- --	
Overall	88.8 15.5	89.9 16.1	92.7 17.7	95.5 19.4	95.3 19.4	87.8 15.3	82.8 12.9	80.8 12.1	77.9 10.6	-- --	

Table 6.--Mean fork length (top row, cm) and weight (bottom row, kg)
of harvested South Pacific albacore by latitude and year.

Year	Latitude									
	0°-5°S	5°-10°S	10°-15°S	15°-20°S	20°-25°S	25°-30°S	30°-35°S	35°-40°S	40°-45°S	0°-45°S
1962	--	96.0	94.4	--	--	--	--	--	--	94.4
	--	19.6	18.7	--	--	--	--	--	--	18.7
1963	--	93.5	94.4	96.2	98.5	96.3	--	--	--	94.6
	--	18.1	18.7	19.9	21.2	19.8	--	--	--	18.8
1964	--	89.5	92.8	95.6	96.0	91.2	--	--	--	91.6
	--	15.9	17.7	19.4	19.8	17.1	--	--	--	17.1
1965	91.2	89.7	92.5	96.8	93.7	88.9	--	--	--	91.5
	16.8	16.0	17.5	20.2	18.5	15.8	--	--	--	17.1
1966	91.5	90.1	93.2	96.8	97.4	90.6	85.4	--	--	91.6
	17.0	16.2	17.9	20.2	20.7	16.7	14.0	--	--	17.1
1967	88.3	89.6	92.1	96.0	97.0	84.9	86.4	--	--	89.5
	15.1	15.9	17.3	19.7	20.3	13.8	14.6	--	--	16.1
1968	88.4	89.3	91.2	94.6	96.7	87.1	79.8	--	--	88.5
	15.2	15.7	16.8	18.8	20.1	14.9	11.4	--	--	15.6
1969	88.5	89.3	92.8	95.5	92.1	87.0	83.6	--	--	89.9
	15.3	15.7	17.7	19.4	17.6	14.8	13.1	--	--	16.2
1970	86.9	88.7	91.2	94.5	88.1	84.9	82.4	78.0	--	87.9
	14.5	15.4	16.9	18.8	15.2	13.7	12.6	10.6	--	15.2
1971	90.7	90.4	92.4	95.3	95.8	89.8	81.6	80.8	--	89.5
	16.5	16.4	17.6	19.3	19.6	16.5	12.6	12.2	--	16.3
1972	91.4	90.1	92.7	94.4	94.3	88.8	86.1	80.3	--	88.6
	17.0	16.3	17.8	18.8	18.8	15.8	14.4	11.9	--	15.8
1973	91.3	90.4	91.9	94.0	94.6	87.1	82.0	82.0	--	86.3
	17.0	16.5	17.4	18.6	18.9	15.0	12.5	12.6	--	14.6
1974	89.1	90.6	92.7	96.2	95.4	91.6	79.9	79.6	77.5	84.5
	15.8	16.6	17.8	20.0	19.5	17.4	11.8	11.5	10.4	13.9
1975	91.6	91.9	95.4	95.0	97.4	93.1	91.0	91.5	80.4	93.0
	17.1	17.2	19.3	19.0	20.6	18.1	17.0	17.1	11.8	18.0
1976	87.4	91.1	95.3	96.7	95.9	89.0	89.1	88.9	--	92.2
	15.0	16.9	19.3	20.3	19.8	16.0	16.0	15.9	--	17.7
All years	88.8	89.9	92.7	95.5	95.3	87.8	82.8	80.8	77.9	--
	15.5	16.1	17.7	19.4	19.4	15.3	12.9	12.1	10.6	--

Table 7.--Mean fork length (top row, cm) and weight (bottom row, kg) of harvested South Pacific albacore by year and vessel nationality.

Year	Japan	Taiwan	Korea	All nations
1962	94.4 18.7	-- --	-- --	94.4 18.7
1963	94.8 18.9	-- --	93.7 18.2	94.6 18.8
1964	91.7 17.2	93.1 17.9	90.4 16.4	91.6 17.1
1965	91.9 17.3	90.5 16.4	91.3 16.9	91.5 17.1
1966	91.4 17.1	91.6 17.1	91.7 17.2	91.6 17.1
1967	87.5 15.2	89.9 16.2	90.7 16.7	89.5 16.1
1968	84.5 13.7	89.4 15.9	89.3 16.0	88.5 15.6
1969	86.6 14.7	90.3 16.3	90.2 16.4	89.9 16.2
1970	84.8 13.8	89.7 16.0	86.6 14.7	87.9 15.2
1971	79.2 12.1	89.4 16.2	89.8 16.5	89.5 16.3
1972	99.9 22.3	91.6 17.2	86.6 14.9	88.6 15.8
1973	-- --	88.9 15.8	84.9 14.0	86.3 14.6
1974	-- --	86.6 15.0	83.1 13.2	84.5 13.9
1975	-- --	93.3 18.1	92.6 17.8	93.0 18.0
1976	-- --	92.6 17.9	92.0 17.6	92.2 17.7

Table 8.--Estimated percentage of total nominal effort (10^3 hooks) by latitude for longliners of Taiwan and Korea based at American Samoa, 1964-77.

Year	Nation	Latitude								Effort (10^3 hooks)
		0°-5°S	5°-10°S	10°-15°S	15°-20°S	20°-25°S	25°-30°S	30°-35°S	35°-40°S	
1964	Taiwan	0	16.9	76.1	5.1	1.3	0.6	0	0	611
	Korea	0	45.9	53.9	0.2	0	0	0	0	1,280
1965	Taiwan	2.7	62.8	21.7	8.7	0.3	3.8	0	0	1,881
	Korea	0.2	54.4	34.5	6.3	1.5	3.1	0	0	4,708
1966	Taiwan	0.4	36.7	36.8	9.5	4.4	12.2	0	0	7,405
	Korea	0.4	44.2	28.4	13.3	0.5	10.1	3.1	0	10,061
1967	Taiwan	1.0	33.2	27.4	14.0	3.1	17.2	4.0	0.1	13,373
	Korea	2.2	31.8	27.5	19.5	2.1	7.1	9.5	0.3	15,378
1968	Taiwan	2.8	52.3	20.3	9.9	3.6	8.7	2.4	0	12,219
	Korea	10.3	41.8	15.6	15.3	1.3	10.0	5.7	0	14,276
1969	Taiwan	4.8	53.1	29.8	6.6	1.4	3.1	1.2	0	9,554
	Korea	12.7	40.5	19.0	10.7	1.5	13.8	1.8	0	20,681
1970	Taiwan	3.6	45.0	29.5	11.0	2.4	6.3	2.2	0	13,746
	Korea	9.5	27.1	16.9	15.6	1.6	16.6	10.8	1.9	20,405
1971	Taiwan	7.4	31.5	21.9	16.0	4.8	10.2	7.5	0.7	12,891
	Korea	6.3	17.4	16.8	21.8	6.3	14.5	13.0	3.9	21,994
1972	Taiwan	5.8	37.7	25.7	12.0	4.9	10.9	2.6	0.5	12,885
	Korea	10.2	21.8	19.2	14.4	2.9	13.7	5.4	12.4	21,603
1973	Taiwan	1.2	32.2	20.9	12.0	4.4	19.5	6.9	2.9	15,541
	Korea	5.6	19.9	13.6	6.8	6.5	19.3	14.4	13.9	32,682
1974	Taiwan	2.3	18.5	20.6	18.0	4.3	10.8	9.0	16.5	14,088
	Korea	16.9	14.2	11.7	12.0	9.7	7.5	9.8	18.2	27,872
1975	Taiwan	3.5	33.0	33.0	8.9	3.4	11.6	2.0	4.6	7,933
	Korea	13.1	44.5	24.1	8.3	4.2	2.8	1.2	1.8	19,876
1976	Taiwan	1.0	17.0	43.0	12.2	2.9	15.7	3.8	4.4	6,267
	Korea	5.4	25.4	18.0	22.8	7.3	17.0	1.9	2.2	22,514
1977	Taiwan	0.8	32.6	24.1	15.2	4.2	13.6	5.9	3.6	9,980
	Korea	7.1	28.8	20.9	11.0	7.8	14.5	6.3	3.6	25,041

Table 9.--Estimated relative fishing power, by nationality of vessel, with respect to the harvest of South Pacific albacore.

Nation	Data sets	Relative fishing power
Japan*	American Samoa	1.00
Taiwan	American Samoa	1.85
Korea	American Samoa	1.25
Japan	Far Seas Fisheries Research Laboratory	0.82

*Standard

Table 10.--Total catch of South Pacific albacore (MT), index of abundance (kg/100 hooks), and estimated total effective effort (10^6 hooks).

Year	Total catch (MT)	Abundance index (kg/100 hooks)	Effective effort (10^6 hooks)
1962	39,479	146.00	27
1963	35,475	85.76	41
1964	24,975	75.39	33
1965	27,450	72.02	38
1966	41,387	63.66	65
1967	45,372	42.56	107
1968	32,355	33.76	96
1969	25,405	41.03	62
1970	30,672	35.42	87
1971	40,605	29.90	136
1972	40,753	21.45	190
1973	49,275	20.19	244
1974	34,911	13.86	252
1975	26,979	13.64	198
1976	36,534	18.00	203
1977	41,371	21.71	191

LONGLINE STATISTICS BY LOCATION
 FAR SEAS FISHERIES RESEARCH LABORATORY DATA (X55972)
 CPUE - AVERAGE OF RATIOS - HOOKS

CODE 505



Figure 1.--Distribution of average catch per hook for Pacific Ocean albacore taken by Japanese longliners, averaged over 1952-76. Boundaries of the index area for the South Pacific albacore stock are also shown.

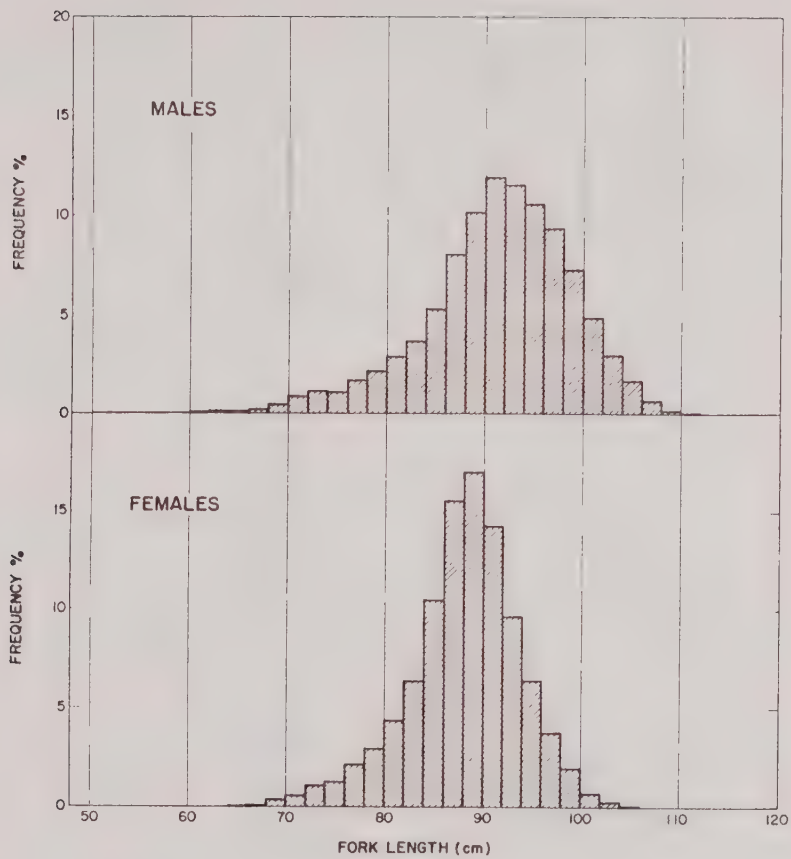


Figure 2.--Fork length composition of South Pacific albacore catches by longline vessels based at Pago Pago, by sex, 1962-70.

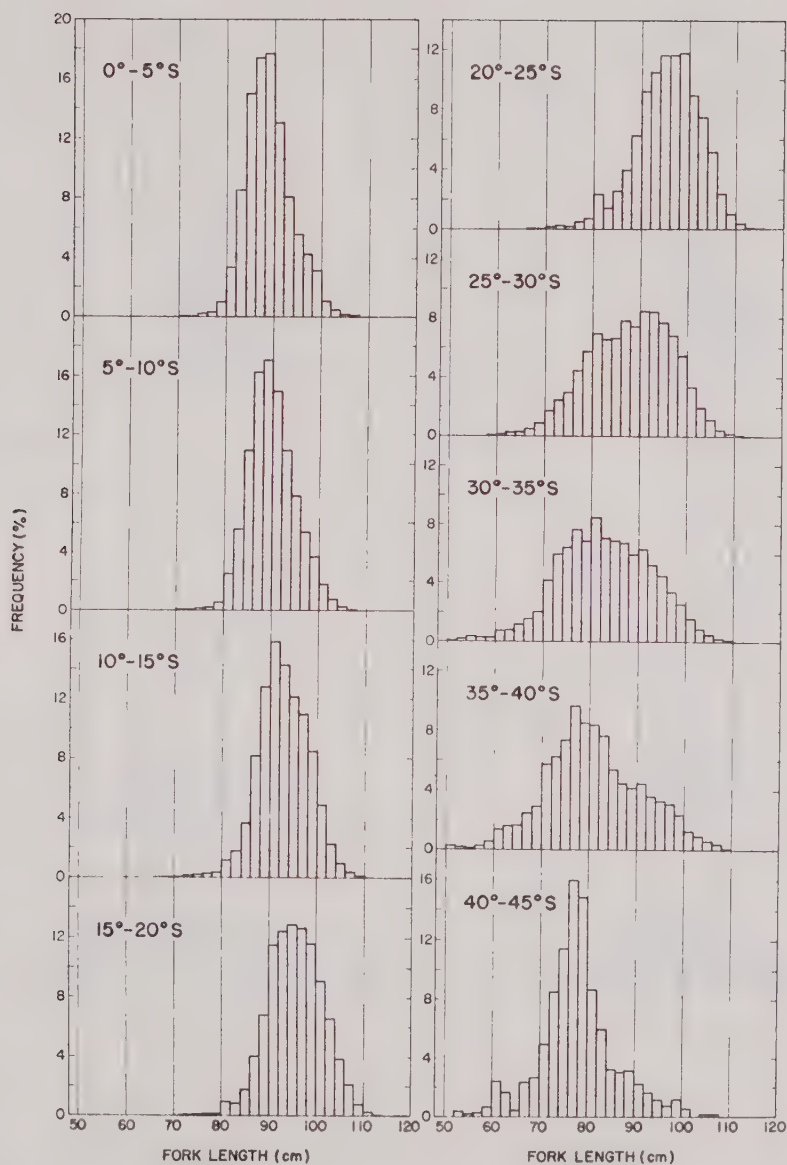


Figure 3.--Fork length composition of South Pacific albacore catches by longline vessels based at Pago Pago, by latitude, 1962-76.

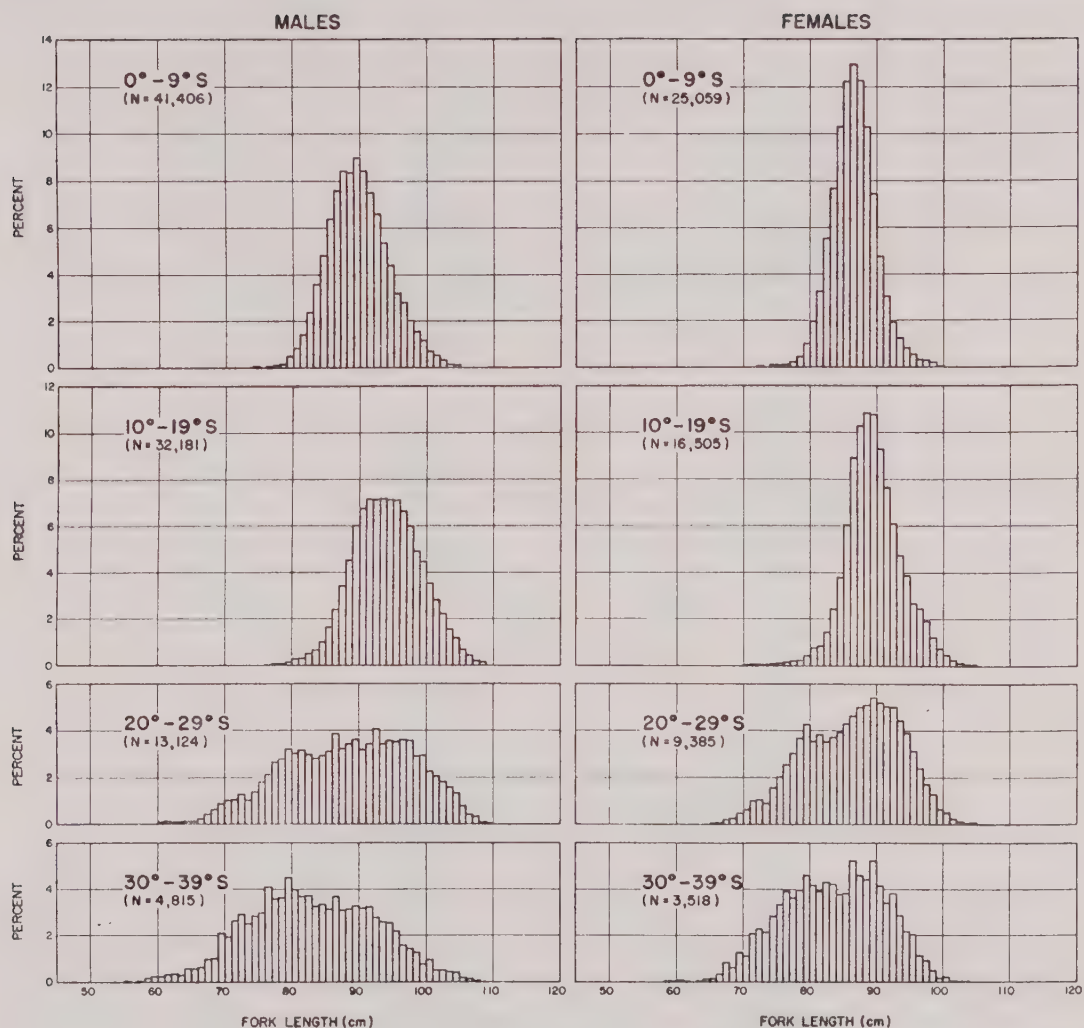


Figure 4.--Fork length composition of South Pacific albacore catches by longline vessels based at Pago Pago, by latitude and sex, 1962-70 (from Yoshida 1975).

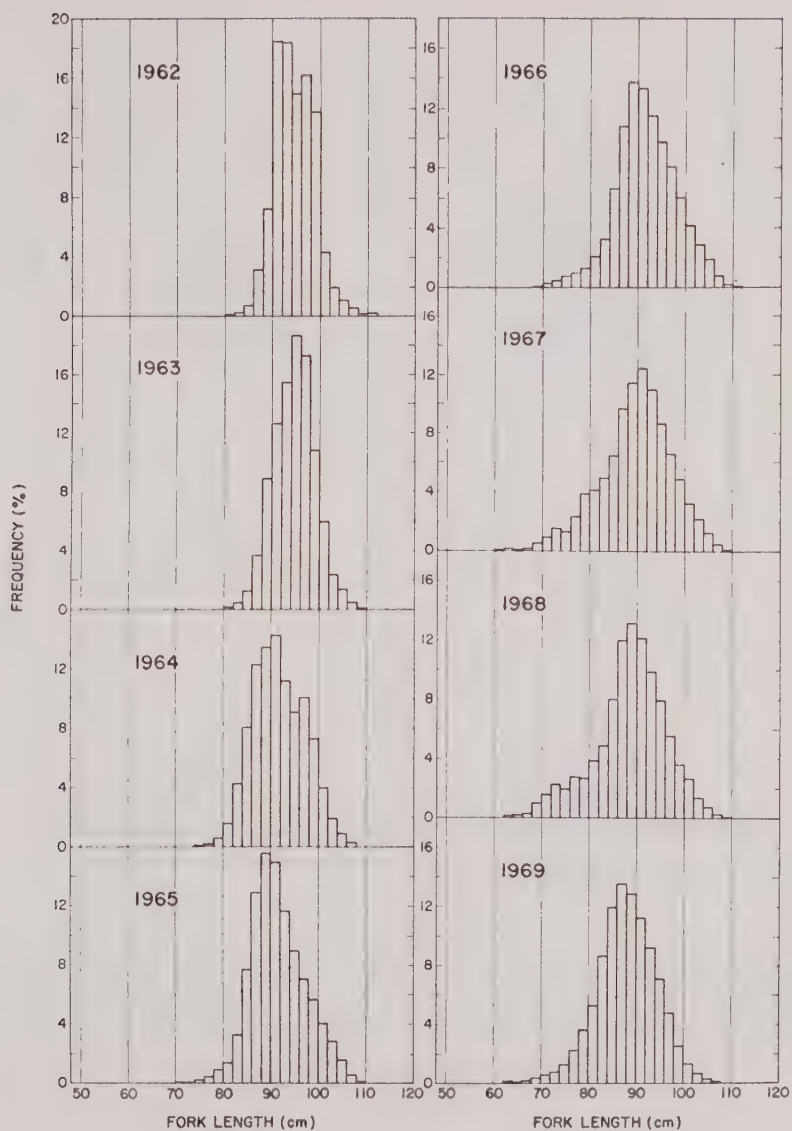


Figure 5.--Fork length composition of South Pacific albacore catches by longline vessels based at Pago Pago, by year, 1962-76.

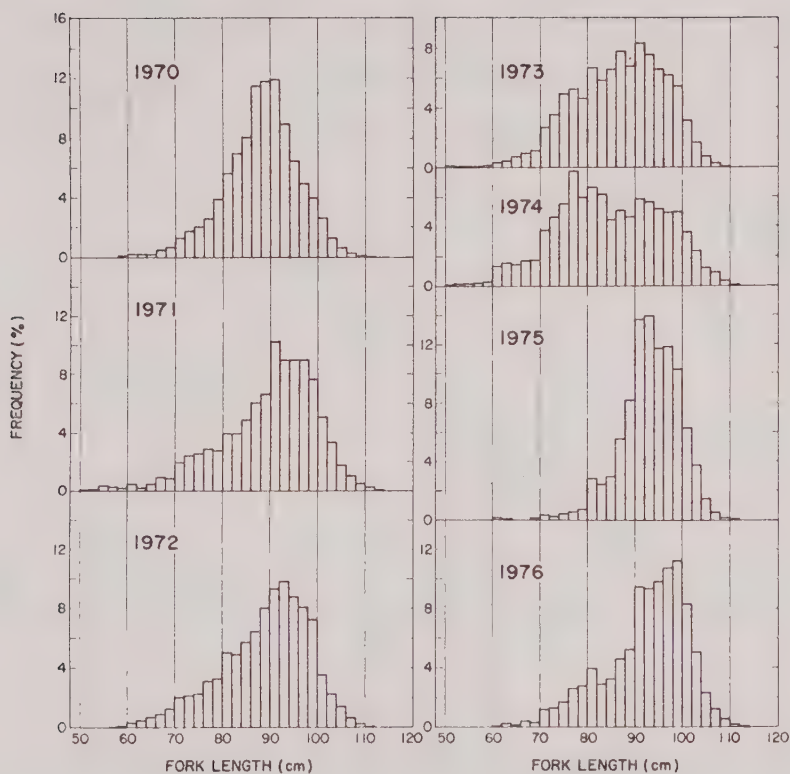


Figure 5.--Fork length composition of South Pacific albacore catches by longline vessels based at Pago Pago, by year, 1962-76.--Continued.

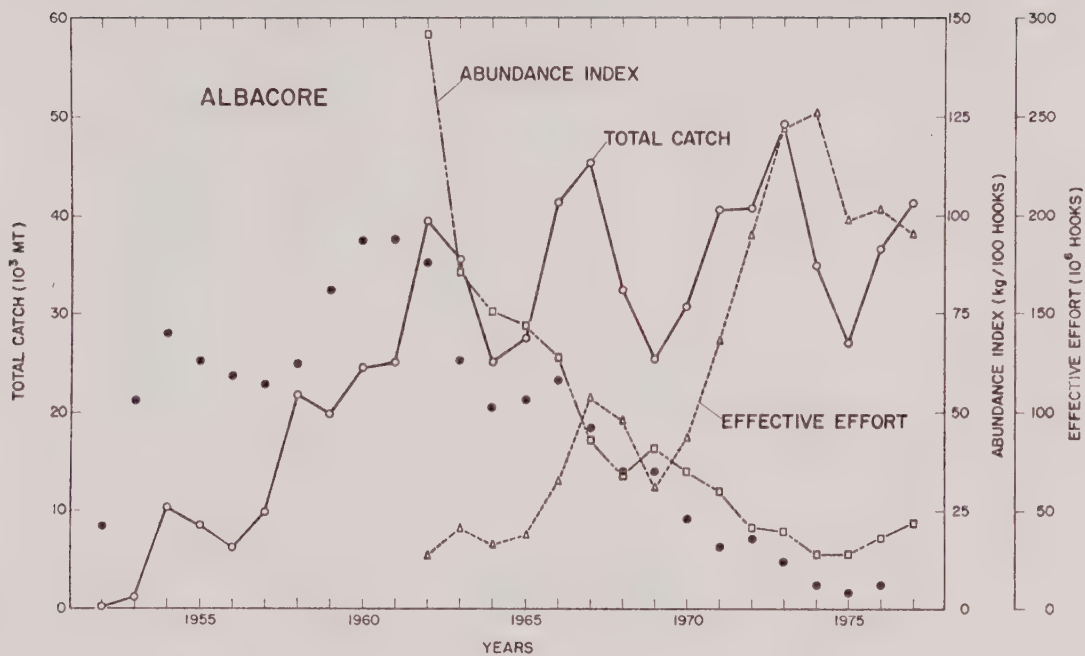


Figure 6.--Estimated total catch (10^3 MT), abundance index (kg/100 hooks), and effective effort (10^6 hooks) for South Pacific albacore. Solid circles denote a second abundance index based on historical Japanese longline statistics.

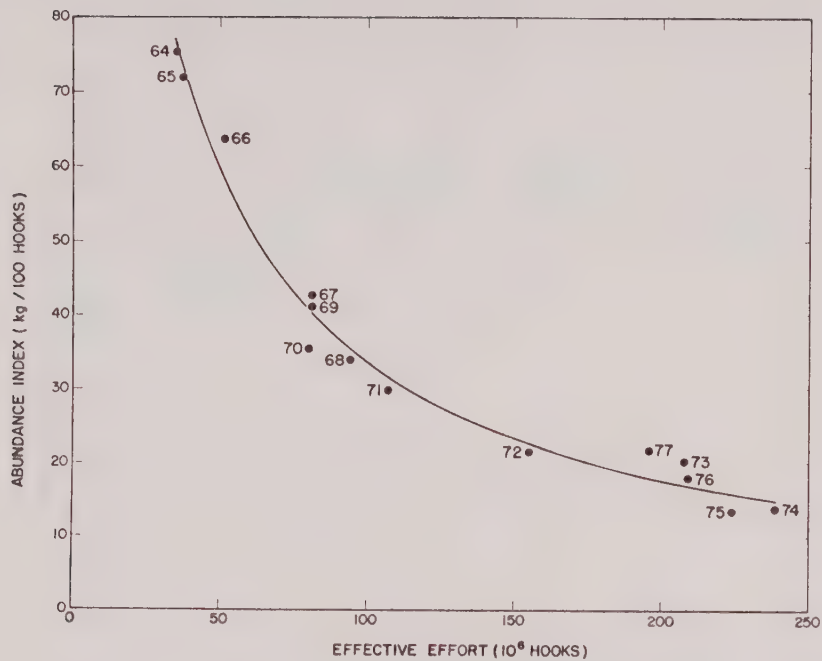


Figure 7.--Fitted production model for South Pacific albacore,
based on 3-year effort averaging.

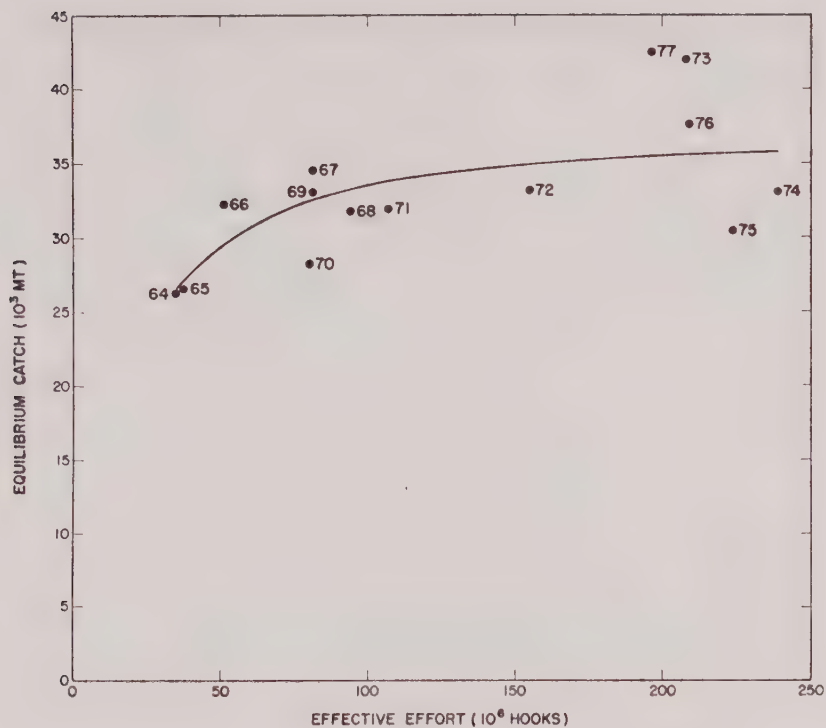


Figure 8.--Projected relationship between equilibrium yield and effective effort for South Pacific albacore, based on production model with 3-year effort averaging.

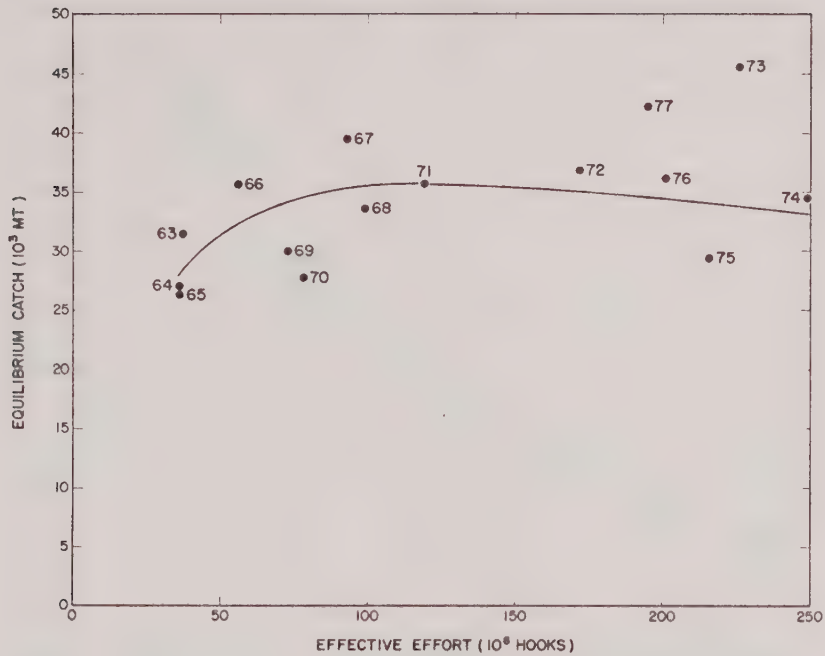


Figure 9.--Projected relationship between equilibrium yield and effective effort for South Pacific albacore, based on production model with 2-year effort averaging.

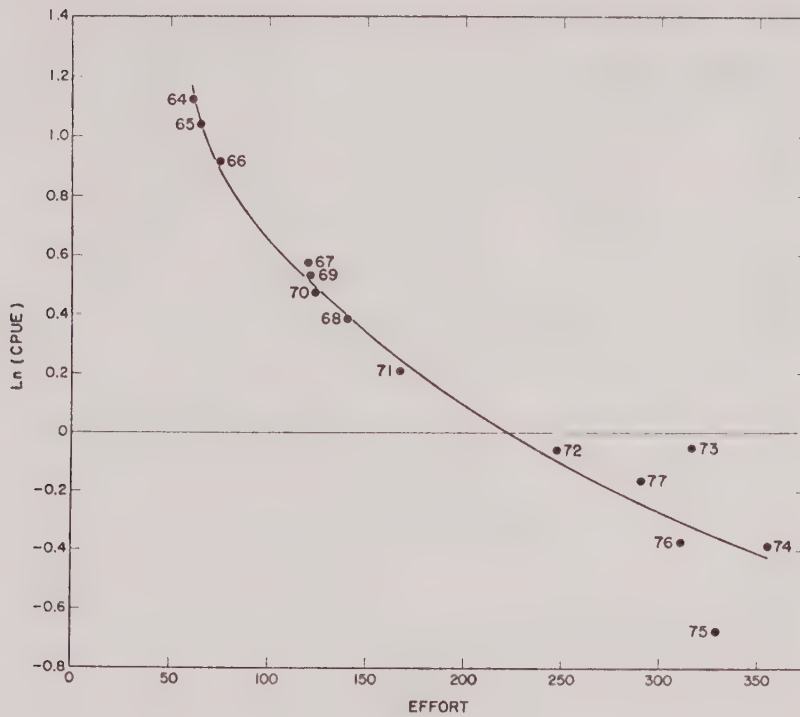


Figure 10.--Relationship between natural logarithm of abundance and effective effort for South Pacific albacore.

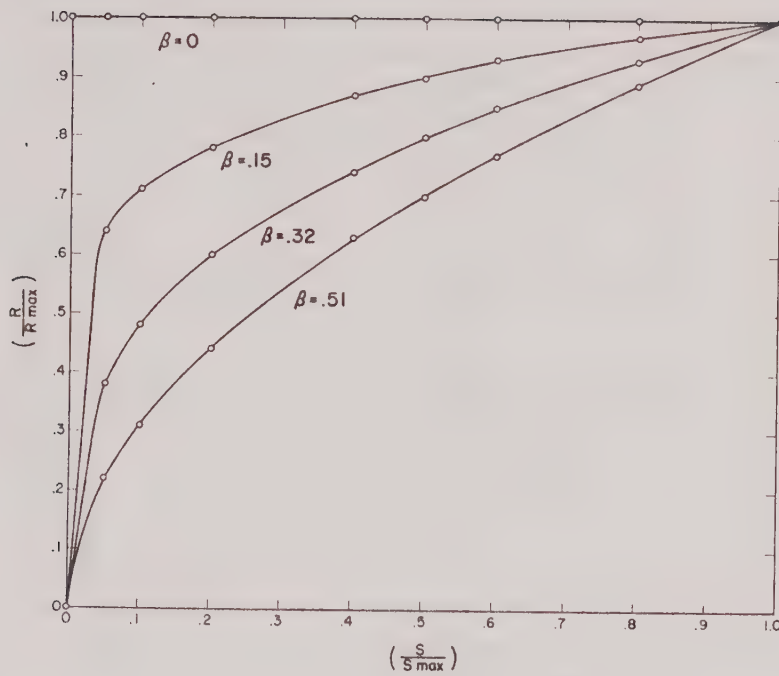


Figure 11.--Hypothetical relationships between recruitment of 2-year olds (R) and the spawning biomass (S) used in the South Pacific albacore simulation model.

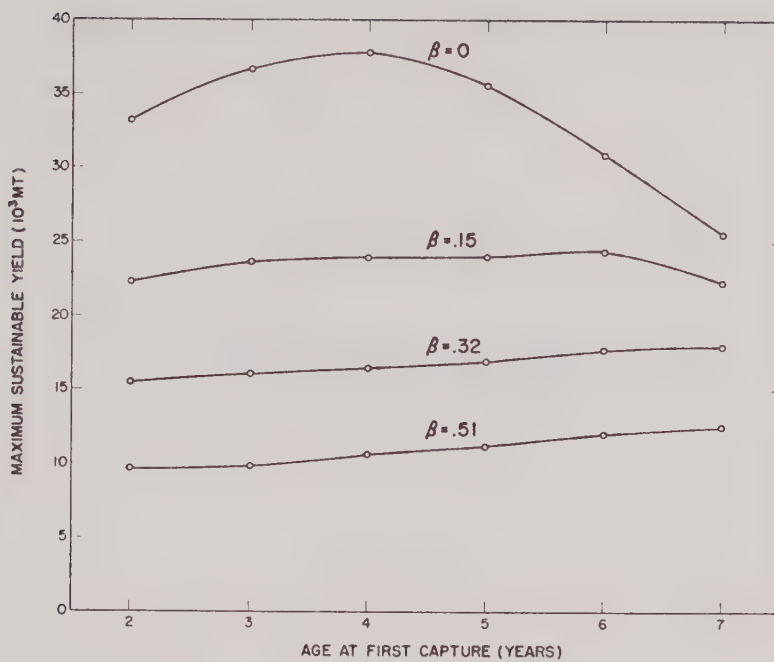


Figure 12.--Predicted relationships between maximum sustainable yield and age at first capture under different assumed stock-recruit relationships for South Pacific albacore.

SOME PRODUCTION MODEL ANALYSES OF TUNA AND BILLFISH STOCKS
IN THE INDIAN OCEAN

Jerry A. Wetherall
Fletcher V. Riggs
Marian Y. Y. Yong

Southwest Fisheries Center
National Marine Fisheries Service, NOAA
Honolulu, Hawaii 96812

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PURPOSE AND SCOPE

This report summarizes some production model analyses of tuna and billfish stocks in the Indian Ocean, using historical total catch statistics and abundance indices computed from longline catch per unit effort data. The purpose is to get a rough idea of the status of the stocks; time and resources did not permit a thorough analysis. Size-composition data were not evaluated, and the completeness and reliability of total catch statistics is open to question. In the case of albacore, yellowfin, and bigeye tuna stocks, the production model results will be compared to earlier assessments by Suda (1973, 1974).

DATA SOURCES

Annual total catch statistics in metric tons (MT) were provided for Japan (1952-77) and Taiwan (1962-77) by S. Ueyanagi of the Far Seas Fisheries Research Laboratory, Shimizu, Japan, and R. T. Yang of National Taiwan University (Tables 1-8). Billfish catches for Taiwan were provided with species combined for 1963-66, so the breakdown by species in these years was estimated by applying the average species composition for 1967 and 1968. No data were available for the catch by longliners from the Republic of Korea except for FAO statistics on tuna catches (1965-76) and the catches of blue marlin, swordfish, and sailfish (1975-76). To estimate the Korean catches of blue marlin for 1965-74 we computed the ratio of blue marlin catch to yellowfin catch during 1975 and 1976 and assumed this ratio prevailed in the earlier years also. To estimate the missing Korean catch figures for other billfish species we computed

the ratio of estimated Korean blue marlin catch to the blue marlin catch by Taiwan in each year and multiplied this times the catch of the given species by Taiwan. These procedures clearly give only a very rough estimation of the Korean catches.

Concerning the catches by countries other than Japan, Taiwan, and Korea, we used statistics from various FAO compilations (FAO 1974, 1975, 1977). These included estimates of longline catches by the U.S.S.R. and Sri Lanka, and surface yellowfin catches by Australia, India, Madagascar, Maldives, Pakistan, Sri Lanka, Democratic Republic of Yemen, Seychelles, and Oman.

Statistics on nominal effort in hooks and associated catch in number of fish by month and 5° square were available for Taiwan (1967-77) and Japan (1952-76).

INDICES OF ABUNDANCE AND EFFECTIVE EFFORT

Annual abundance indices for each species were constructed in the manner described by Wetherall et al. (1979), using the detailed Japanese catch and nominal effort statistics and average weight estimates computed over the entire ocean (Table 9). Index areas were selected after consideration of stock structure information in Suda (1974) and examination of plots of spatial variation in average catch rates (Figures 1 through 8). Boundaries of the selected index areas are as follows:

<u>Species</u>	<u>Latitude</u>	<u>Longitude</u>
Albacore	0°-45°S	20°-120°E
Yellowfin tuna	15°N-15°S	40°-100°E
Bigeye tuna	15°N-35°S	40°-110°E
Blue marlin	10°N-25°S	40°-100°E
Striped marlin	20°N-30°S	20°-125°E
Black marlin	20°N-25°S	90°-125°E
Swordfish (1)	20°N-15°S	45°-100°E
(2)	20°S-45°S	20°-55°E
Sailfish (1)	20°N-5°S	45°-100°E
(2)	0°-30°S	35°-50°E

Effective effort was computed by dividing the abundance indices into appropriate annual total catch statistics (Tables 10 and 11; Figures 9 through 14). Abundance indices and effective effort were standardized to Japanese data in the first year of each time series.

PRODUCTION MODELS

The PROFIT program by Fox (1975) was used to fit production models to abundance indices and the associated measures of effective effort. Effort was averaged over 1-, 2-, 3-, and 4-year periods to approximate equilibrium conditions.

Results are summarized in Tables 12 and 13, and Figures 17 through 22, and are evaluated here species by species:

Albacore

The total albacore catch rose steadily in the first decade of the fishery to about 17,700 MT and then fluctuated rather markedly after 1962 (Table 10). The highest catch of 28,250 MT was taken in 1974. The abundance index tripled in the first few years of the fishery, but has since declined steadily to less than one-tenth its peak value (Figure 9).

The production model analysis (Table 12) gives a best estimate of maximum sustainable yield (MSY) equal to about 17,800 MT at an infinitely high effective effort. However, the yield curve is very flat over a wide range of effort, and an average catch nearly equal to the MSY could apparently be achieved at an effort significantly less than the 1976 level (Figure 17).

Suda (1973) estimated the MSY for Indian Ocean albacore to be in the range of 20,000-25,000 MT. We believe much of the discrepancy between our estimate and his can be accounted for by the tendency of his total catch estimates to be greater than ours. At any rate, the conclusion of both analyses is that the stock is fully harvested. The failure of the total catch to increase significantly in spite of the expansion of fishing effort south of lat. 30°S during the 1960's and 1970's (Table 14) is consistent with Suda's yield per recruit assessments (and similar analyses on other albacore stocks) which suggest no gain in yield per recruit from harvesting the younger fish found in the more southerly waters.

Bigeye tuna

Total catch of bigeye tuna in the Indian Ocean increased fairly steadily until 1968, when almost 39,000 MT were taken, and then fell in the next 5 years to only about 15,000 MT in 1973. It then roughly doubled, ranging between 26,448 to 38,359 MT during the next 3 years. The decline in total catch between 1968 and 1973 was experienced by all three longline fleets, whereas the increase in total catch estimates during 1974-76 was due mostly to a reported rise in the Korean catch (Table 2). The abundance index for bigeye has fluctuated moderately but has shown a definite downward trend since the inception of longlining. However, the apparent abundance is still about 50% of its initial level (Figure 10).

The production model analysis (Table 12) gives two different results, depending on the number of years over which effective effort is averaged. With 1- or 2-year averaging, the estimated MSY is 59,000-60,000 MT at infinitely high effort. On the other hand, smoothing by 3 or 4 years gives an MSY of about 30,600 to 32,500 MT at effort levels only slightly greater than recent ones (Figure 18). The analysis is quite sensitive to the choice of smoothing period because there are no observations to clearly define either the right hand side of a dome-shaped production curve or the flat top of an asymptotic one. Suda had similar difficulties in establishing the behavior of the yield curve and high efforts. He concluded that MSY was about 30,000 MT for the whole Indian Ocean, and could be realized by roughly doubling effective effort over the 1970-71 level. This is consistent with our findings when the 3- or 4-year effort averaging is chosen.

Yellowfin tuna

During the early years of Japanese longlining in the Indian Ocean, yellowfin tuna were a primary target and the total catch of yellowfin tuna rose quickly as effort was concentrated in good yellowfin tuna grounds. The peak Japanese yellowfin tuna catch of about 52,000 MT was in 1962, and annual Japanese harvests varied widely from 25,000-50,000 MT throughout the 1960's. During the 1970's the Japanese catch has been much lower, well under 10,000 MT in most years (Table 3) as effort has shifted away from the equatorial yellowfin tuna grounds. The catch by Taiwan reached high levels in 1968-71, but has been less than 5,000 MT in most other years. According to FAO statistics, the longline catch of Indian Ocean yellowfin tuna since 1972 has been dominated by Korea.

Besides the longline fishery for yellowfin tuna there is a substantial surface fishery. While the surface catch is very poorly documented, various FAO records show that it has increased dramatically during the 1970's, with catches in 1975 and 1976 exceeding 20,000 MT (not including the harvest by Sri Lanka which was probably about 5,000 MT each year). The surface fishery takes yellowfin tuna mostly 2 years old or younger (FAO 1974) whereas the longliners harvest predominantly 2- and 3-year olds (Suda 1974). In recent years the decline in total longline harvest has been balanced by the increase in surface catch (Table 3).

While it has been hypothesized that at least two stocks of Indian Ocean yellowfin tuna exist, east and west of approximately long. 90°E, we were unable to break our total catch statistics down into the two hypothesized regions. Therefore we fit a production model to the aggregated statistics for the whole ocean. The abundance index for the

region has shown a steady decline since 1954 to levels perhaps only one-fifth or one-sixth as high as at the inception of fishing (Figure 11). With smoothing periods of 2 or 3 years, the MSY is estimated to be about 43,000-45,400 MT. This can be compared to Suda's estimate of about 35,000 MT. Under all averaging periods considered the equilibrium yield curve (Figure 19) is essentially asymptotic to MSY, and the analysis suggests that no substantial increase in average annual yield can be achieved. From 1970 to 1976 the effective effort by longliners has been relatively steady while effective effort by surface fleets has quadrupled. Although the stock size has declined during this period, the total catch has been relatively constant. The fraction taken by surface fisheries has grown while the longline catch has diminished.

Blue Marlin

Information on the population biology of blue marlin in the Indian Ocean is virtually non-existent. Assuming a single stock, our abundance index for blue marlin suggests a fairly steady decline since the beginning of Japanese longlining in 1952, except for a momentary increase during 1972-74 (Figure 12). Total catch apparently peaked in 1956 at about 5,000 MT, fluctuated between 2,600 and 4,300 MT thereafter through 1970, and has usually been less than 2,500 MT in more recent years. Note that the Korean catch totals were roughly estimated in all years except 1975 and 1976 (Table 4).

The production models for blue marlin (Table 13) suggest an MSY of 3,400-3,600 MT achievable at an effort substantially less than any recent level (Figure 20), but the curves fit poorly. There may be significant errors in our total catch estimates.

Striped Marlin

As with blue marlin, no assessment work has yet been done with Indian Ocean striped marlin. However, the distribution and biology of striped marlin taken by the Japanese tuna longline fishery in the Indian Ocean has been studied, most recently by Pillai and Ueyanagi (1978).

Our statistics (Table 5) show that the total catch fluctuated between 800 and 2,400 MT annually from 1954 through 1964. Relatively high catches were taken in the following 6 years. During the 1970's the estimated catch dropped off considerably until 1976. The decline of Japanese longline catches during the 1970's is due in part to a shift of effort to more southerly waters where striped marlin are much less abundant. The Korean catches are estimated very roughly, as mentioned earlier.

The abundance index for striped marlin, assuming a single stock, shows a fair degree of annual variation, but the overall trend in stock size since the beginning of longlining is downward to a level perhaps one-fourth of the original abundance. The index has increased steadily over 1972-76 (Figure 13). The production model analysis for striped marlin gives an MSY of about 3,500 MT at an effort level above any yet experienced. The yield curve is very flat over a broad range of efforts (Figure 21).

Black Marlin

The total Indian Ocean catch of black marlin ranged from 1,100 to 1,600 MT during 1954-67, then reached the highest levels on record during 1968-69. The average catch during the 1970's has been substantially

lower (Table 5, Figure 14). As in the Pacific Ocean, black marlin abundance is apparently greatest in coastal regions. The highest catch rates are seen in the eastern Indian Ocean. On the basis of catch rates, other concentrations also exist off southern Africa and Saudi Arabia.

The stock structure of black marlin is unknown. There may be more than one stock in the Indian Ocean, and interactions between the species in the eastern Indian Ocean and western Pacific (Shomura 1978). For the purposes of our analysis we considered the aggregate catch of black marlin in the Indian Ocean and assumed trends in the index for the eastern area were representative of trends in average abundance throughout the ocean. The index (Figure 14) shows a definite declining trend from the early 1950's until the present. The estimated MSY (Table 13) is 1,400-1,500 MT. Optimum effort is less than recent levels, but the yield-effort curve is quite flat (Figure 22). The equilibrium data points for 1972-76 are clustered below the expected yield curve, whereas the points for 1968-71 are above it, suggesting the possibility of some systematic bias in the above estimates.

Swordfish

While the distribution of catch rates in Figure 7 does not show it clearly, due to the scaling chosen for the plot, there seem to be two areas where densities of swordfish are relatively high. We constructed abundance indices in both areas (Table 11, Figure 15). Total catch of swordfish increased steadily from the early 1950's up through the 1960's, but has decreased during the 1970's. Both indices suggest rather marked variations in abundance, although an early decline in stock size through

the mid-1960's is apparent. Since then the indices have been erratic with no evidence of sustained stock decrease in spite of a relatively large increase in average annual catch. The data suggest that longlining has had no significant impact on the swordfish population, (for example, stock size has not been reduced below about 65% of its original level), so no production model analysis was attempted.

Sailfish

The "sailfish" catch contains an unknown percentage of shortbill spearfish, the proportion of spearfish being higher in offshore areas. However, the population dynamics of these species may be rather similar, so we may assume similar responses to exploitation. Two index areas were selected, based on average catch rates. As shown in Table 11 and Figure 16, total catch in the Indian Ocean climbed from about 200 MT in 1954 to nearly 2,000 MT in 1968. Since then it has declined, and the reported longline catch was less than 1,000 MT per year during 1974-76.

The stock abundance indices show considerable variability, with much higher variation in the more northerly index area. In general a long-term increase in apparent abundance of sailfish is evident, particularly in the southern index region. In neither case is there any indication that the stock has been affected by fishing, and we conclude that the potential yield for sailfish is much higher than the maximum annual catch taken thus far.

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Table 1.--Estimated annual catches (metric tons) of Indian Ocean albacore, by nation and year.

Year	Japan ¹	Taiwan ²	Korea ³	U.S.S.R. ⁴	Total
1952	67				67
1953	1,099				1,099
1954	2,759				2,759
1955	3,302				3,302
1956	4,821				4,821
1957	4,664				4,664
1958	6,285				6,285
1959	10,412				10,412
1960	11,066				11,066
1961	15,438				15,438
1962	17,668				17,668
1963	12,546	74			12,620
1964	17,874	210	--		18,084
1965	11,375	22	500	500	12,397
1966	13,130	2,646	500	1,000	17,276
1967	14,098	5,205	2,900	1,500	23,703
1968	10,034	6,135	600	600	17,369
1969	8,546	9,427	3,000	900	21,873
1970	4,684	6,436	3,000	1,100	15,220
1971	3,140	4,346	2,100	600	10,186
1972	1,257	6,278	3,600	600	11,735
1973	1,835	10,570	9,000	900	22,305
1974	2,606	15,438	9,206	⁵ 1,000	28,250
1975	1,168	5,794	3,243	⁵ 1,000	11,205
1976	1,166	8,924	3,847	⁵ 1,000	14,937
1977	404	9,502	--	--	--
1978	--	7,824	--	--	--

¹Courtesy of S. Ueyanagi, Far Seas Fisheries Research Laboratory, Japan.

²Courtesy of R. T. Yang, National Taiwan University, Taiwan

³FAO (1977).

⁴FAO (1974, 1975)

⁵Guessed value.

Table 2.--Estimated annual catches (metric tons) of Indian Ocean
bigeye tuna, by nation and year.

Year	Japan ¹	Taiwan ²	Korea ³	Sri Lanka ⁴	U.S.S.R. ⁴	Yemen ³	Total
1952	1,500						1,500
1953	3,600						3,600
1954	7,900						7,900
1955	6,060						6,060
1956	8,040						8,040
1957	12,400						12,400
1958	11,300						11,300
1959	8,900						8,900
1960	15,700						15,700
1961	13,500						13,500
1962	18,700	1,226					19,926
1963	12,400	1,653			100		14,153
1964	16,700	1,771	--		400		18,871
1965	18,200	1,362	100		500		20,162
1966	22,600	2,175	100	100	1,400		26,375
1967	22,400	2,324	200	100	2,000		27,024
1968	24,600	7,209	5,400	200	1,300		38,709
1969	15,000	7,980	10,000	200	1,100		34,280
1970	13,600	7,604	11,000	100	1,800		34,104
1971	11,700	5,701	4,100	100	1,100		22,701
1972	8,800	4,143	4,300	100	800		18,143
1973	5,700	2,955	5,600	100	600		14,955
1974	7,700	4,448	13,300	--	⁵ 1,000		26,448
1975	8,500	4,005	24,691	--	⁵ 1,000	163	38,359
1976	2,900	3,165	21,018	--	⁵ 1,000	163	28,246
1977	5,200	5,170	--	--	--	--	--
1978	--	1,601	--	--	--	--	--

¹Courtesy of S. Ueyanagi, Far Seas Fisheries Research Laboratory, Japan.

²Courtesy of R. T. Yang, National Taiwan University, Taiwan.

³FAO (1977).

⁴FAO (1974, 1975).

⁵Guessed value.

Table 3.--Estimated annual catches (metric tons) of Indian Ocean yellowfin tuna, by nation and year.

Year	Longline catch					Total longline	Surface catch								Total surface	Grand total	
	Japan ¹	Taiwan ²	Korea ³	U.S.S.R. ⁴	Sri Lanka ⁵		Australia ⁶	Bangladesh ⁷	India ⁸	Madagascar ⁹	Maldives ¹⁰	Pakistan ¹¹	Sri Lanka ¹²	Seychelles ¹³			Yemen ¹⁴
1952	8,858					8,858											8,858
1953	13,258					13,258											13,258
1954	24,883					24,883											24,883
1955	27,875					27,875											27,875
1956	38,641					38,641											38,641
1957	36,036					36,036											36,036
1958	25,727					25,727											25,727
1959	24,428					24,428											24,428
1960	40,292					40,292											40,292
1961	34,551					34,551											34,551
1962	51,665	3,468				55,133											55,133
1963	25,888	3,402		100		29,390											29,390
1964	24,752	2,859		300	200	28,111											28,111
1965	27,579	2,180	0	900	200	30,859		100	800		500		2,000				30,111
1966	44,106	4,368	100	2,600	200	51,374		200	1,000		1,500		1,700				51,374
1967	31,597	3,380	200	3,100	300	38,577		100	1,000		1,700		2,600				38,577
1968	50,475	22,646	4,000	2,700	400	80,221		100	1,300		1,700		4,100				80,221
1969	25,228	21,089	7,000	1,600	400	55,317		100	1,100		1,800		3,800				55,317
1970	14,459	11,865	8,000	2,000	300	36,624			500		1,200		4,000				36,624
1971	13,471	16,536	6,500	1,500	200	38,207	100		200		1,300		3,800				38,207
1972	8,880	8,833	9,600	1,600	100	29,013	100		200	200	5,000		5,100				29,013
1973	7,470	4,216	9,200	900	100	21,886			200	500	5,200		5,000				21,886
1974	7,935	3,147	11,563			22,645			200	1,700	4,500						22,645
1975	8,577	3,371	11,694			23,642					4,200						23,642
1976	3,507	2,545	12,848			18,900					4,800						18,900
1977	3,521	6,690															
1978		2,114															

¹Courtesy of S. Ueyanagi, Far Seas Fisheries Research Laboratory, Japan.

²Courtesy of R. T. Yang, National Taiwan University, Taiwan.

³FAO (1977).

⁴FAO (1974, 1975).

⁵Incomplete.

Table 4.--Estimated annual catches (metric tons) of Indian Ocean blue marlin, by nation and year.

Year	Japan ¹	Taiwan ²	Korea ³	Total
1952	800			800
1953	2,000			2,000
1954	3,300			3,300
1955	3,600			3,600
1956	4,980			4,980
1957	3,800			3,800
1958	4,100			4,100
1959	4,300			4,300
1960	3,700			3,700
1961	3,200			3,200
1962	3,100			3,100
1963	1,800	834		2,634
1964	2,900	840		3,740
1965	3,300	578	0	3,878
1966	3,300	446	8	3,754
1967	3,400	658	16	4,074
1968	2,300	1,410	326	4,036
1969	1,800	1,504	571	3,875
1970	1,200	1,185	653	3,038
1971	1,000	1,002	530	2,532
1972	900	826	783	2,509
1973	600	540	751	1,891
1974	900	526	944	2,370
1975	700	447	1,130	2,277
1976	300	343	872	1,515
1977	300	452	--	--

¹Courtesy of S. Ueyanagi, Far Seas Fisheries Research Laboratory, Japan.

²Courtesy of R. T. Yang, National Taiwan University, Taiwan; 1963-66 estimated.

³1965-74 estimated; see text. 1975-76 from FAO (1977).

Table 5.--Estimated annual catches (metric tons) of Indian Ocean striped marlin, by nation and year.

Year	Japan ¹	Taiwan ²	Korea ³	Total
1952	100			100
1953	300			300
1954	800			800
1955	780			780
1956	1,740			1,740
1957	1,800			1,800
1958	1,700			1,700
1959	2,100			2,100
1960	2,000			2,000
1961	2,400			2,400
1962	1,800			1,800
1963	1,300	483		1,783
1964	1,400	486		1,886
1965	3,000	335	0	3,335
1966	3,900	258	5	4,163
1967	4,200	257	6	4,463
1968	2,300	923	213	3,436
1969	2,200	1,833	696	4,729
1970	1,700	909	501	3,110
1971	1,000	714	378	2,092
1972	800	365	346	1,511
1973	500	258	359	1,117
1974	1,400	501	899	2,800
1975	900	344	870	2,114
1976	500	819	2,082	3,401
1977	500	1,401	--	--

¹Courtesy of S. Ueyanagi, Far Seas Fisheries Research Laboratory, Japan.

²Courtesy of R. T. Yang, National Taiwan University; 1963-66 estimated.

³Estimated, see text.

Table 6.--Estimated annual catches (metric tons) of Indian Ocean
black marlin, by nation and year.

Year	Japan ¹	Taiwan ²	Korea ³	Total
1952	300			300
1953	800			800
1954	1,100			1,100
1955	1,080			1,080
1956	1,500			1,500
1957	1,400			1,400
1958	1,200			1,200
1959	1,200			1,200
1960	1,700			1,700
1961	1,400			1,400
1962	1,800			1,800
1963	1,100	351		1,451
1964	1,300	354		1,654
1965	1,100	244	0	1,344
1966	1,200	188	3	1,391
1967	1,300	242	6	1,548
1968	1,700	617	143	2,460
1969	1,300	753	286	2,339
1970	900	609	336	1,845
1971	700	481	254	1,435
1972	200	356	337	893
1973	200	213	296	709
1974	400	337	605	1,342
1975	500	192	495	1,187
1976	200	78	198	476
1977	100	120	--	--

¹Courtesy of S. Ueyanagi, Far Seas Fisheries Research Laboratory, Japan.

²Courtesy of R. T. Yang, National Taiwan University, Taiwan; 1963-66 estimated.

³Estimated, see text.

Table 7.--Estimated annual catches (metric tons) of Indian Ocean swordfish, by nation and year.

Year	Japan ¹	Taiwan ²	Korea ³	Total
1952	<100			<100
1953	100			100
1954	200			200
1955	240			240
1956	480			480
1957	300			300
1958	500			500
1959	500			500
1960	600			600
1961	700			700
1962	900			900
1963	700	351		1,051
1964	900	354		1,254
1965	1,100	244	0	1,344
1966	1,200	188	3	1,391
1967	1,600	226	5	1,831
1968	1,200	626	145	1,971
1969	1,200	786	298	2,284
1970	1,000	809	446	2,255
1971	800	512	271	1,583
1972	800	387	367	1,554
1973	500	271	377	1,148
1974	600	419	752	1,771
1975	700	291	244	1,235
1976	300	371	398	1,069
1977	300	400	--	--

¹Courtesy of S. Ueyanagi, Far Seas Fisheries Research Laboratory, Japan.

²Courtesy of R. T. Yang, National Taiwan University; 1963-66 estimated.

³1965-74 estimated; see text. 1975-76 from FAO (1977).

Table 8.--Estimated annual catches (metric tons) of Indian Ocean sailfish, by nation and year.

Year	Japan ¹	Taiwan ²	Korea ³	Total
1952	<100			<100
1953	100			100
1954	200			200
1955	180			180
1956	300			300
1957	300			300
1958	400			400
1959	500			500
1960	500			500
1961	500			500
1962	800			800
1963	500	175		675
1964	600	177		777
1965	1,100	122	0	1,222
1966	1,200	94	2	1,296
1967	1,900	70	2	1,972
1968	1,200	349	81	1,630
1969	700	353	134	1,187
1970	600	268	148	1,016
1971	800	359	190	1,349
1972	600	280	265	1,145
1973	300	54	75	429
1974	300	126	226	652
1975	200	511	280	991
1976	200	261	140	601
1977	<100	29	--	--

¹Courtesy of S. Ueyanagi, Far Seas Fisheries Research Laboratory, Japan.

²Courtesy of R. T. Yang, National Taiwan University, Taiwan; 1963-66 estimated.

³1965-1974 estimated; see text. 1975-76 from FAO (1977).

Table 9.--Estimated mean weights (kg) of tunas and billfishes caught in the Indian Ocean by longliners of Japan and Taiwan.

Year	Albacore	Bigeye tuna	Yellowfin tuna	Blue marlin	Striped marlin	Black marlin	Swordfish	Sailfish
<u>Japan</u>								
1952	18.8	53.4	52.0	67.8	32.8	36.4	--	--
1953	19.2	54.8	48.1	63.8	40.5	37.8	42.4	21.2
1954	19.4	54.8	48.6	63.3	37.7	36.3	49.4	33.3
1955	19.7	32.1	26.3	64.6	37.5	35.5	46.7	23.5
1956	19.9	27.3	29.0	64.7	37.0	35.5	43.8	25.2
1957	20.1	54.1	46.8	65.2	36.1	36.0	36.4	23.9
1958	20.8	55.9	43.7	64.6	36.5	37.6	39.7	28.5
1959	19.8	51.0	39.2	65.4	37.0	37.2	42.5	27.4
1960	19.3	48.5	39.9	64.6	38.0	35.5	38.5	27.3
1961	19.9	49.8	39.7	65.0	36.9	35.5	41.5	26.9
1962	17.5	43.3	36.6	64.7	37.5	37.0	38.8	26.0
1963	17.5	45.3	37.3	64.2	38.5	36.6	38.9	26.2
1964	17.7	48.9	39.9	66.1	36.8	36.5	41.2	26.3
1965	18.1	46.1	33.9	65.2	36.8	35.6	42.5	25.9
1966	17.5	46.1	36.9	65.3	37.0	36.3	40.8	24.2
1967	16.6	43.0	34.6	65.7	36.7	36.2	40.2	24.5
1968	16.2	44.5	28.8	66.0	36.2	35.9	38.2	24.3
1969	14.6	38.5	30.8	66.8	37.1	35.9	37.8	25.1
1970	15.6	39.4	36.3	66.3	37.7	34.6	35.9	27.4
1971	13.9	39.7	27.0	68.1	35.1	38.5	33.0	25.0
1972	13.2	41.3	29.7	64.4	37.7	33.1	38.9	26.6
1973	12.7	39.9	42.9	68.2	34.3	35.8	29.1	29.6
1974	14.4	39.3	37.1	67.1	37.3	36.4	33.1	27.7
1975	14.7	41.2	31.0	67.3	36.0	40.5	34.4	30.0
1976	11.9	39.0	33.5	65.7	35.0	41.7	29.5	31.2
1977 ¹	12.2	41.3	33.5	75.0	38.5	33.3	37.5	--
<u>Taiwan</u>								
1967	15.5	36.4	32.4	75.5	45.3	68.5	42.5	30.1
1968	15.3	34.3	22.2	72.4	40.1	58.0	45.0	26.7
1969	16.9	32.6	27.4	71.9	40.4	61.6	45.8	26.5
1970	17.2	33.3	28.8	69.4	42.5	47.8	40.7	23.3
1971	19.1	33.4	21.0	66.0	39.7	64.0	42.3	25.0
1972	17.5	32.0	26.1	67.1	37.8	61.2	41.9	21.8
1973	14.9	31.4	30.8	69.7	42.3	71.0	45.5	27.2
1974	16.1	34.6	30.5	65.5	42.1	52.3	44.2	24.6
1975	17.5	32.6	26.6	60.3	40.0	49.1	28.8	28.3
1976	15.9	28.3	28.9	31.8	40.8	61.9	45.5	14.6
1977	15.3	31.9	32.0	65.5	41.6	62.2	41.4	26.0

¹1977 average weights for Japan estimated.

Table 10.--Estimated total catch (MT) relative abundance (kg/100 hooks) and effective effort (10^6 hooks) for Indian Ocean albacore, bigeye tuna, and yellowfin tuna.

Year	Albacore			Bigeye tuna			Yellowfin tuna		
	Catch (MT)	Abundance index (kg/100 hooks)	Effective effort (10^6 hooks)	Catch (MT)	Abundance index (kg/100 hooks)	Effective effort (10^6 hooks)	Catch (MT)	Abundance index (kg/100 hooks)	Effective effort (10^6 hooks)
1952	67	21.24	0.32						
1953	1,099	33.56	3.30	3,600	58.62	6.14	13,258	164.33	8.07
1954	2,759	42.52	6.51	7,900	67.06	11.77	24,883	172.62	14.41
1955	3,302	63.84	5.19	6,060	41.85	14.47	27,875	102.12	27.28
1956	4,821	37.46	12.92	8,040	34.92	22.97	38,641	97.93	39.44
1957	4,664	42.36	11.05	12,400	60.19	20.59	36,036	96.09	37.49
1958	6,285	26.29	24.00	11,300	67.37	16.76	25,727	75.44	34.09
1959	10,412	18.63	56.09	8,900	47.15	18.86	24,428	78.74	31.01
1960	11,066	14.78	75.16	15,700	54.71	28.68	40,292	76.44	52.69
1961	15,438	16.48	94.04	13,500	44.81	30.11	34,551	62.19	55.53
1962	17,668	11.60	152.90	19,926	41.92	47.51	55,133	52.20	105.58
1963	12,620	7.37	171.88	14,153	46.63	30.12	29,390	37.32	78.72
1964	18,084	9.56	189.88	18,871	44.75	41.25	30,111	32.30	93.18
1965	12,397	7.11	167.87	20,162	35.81	54.87	34,459	27.33	126.05
1966	17,276	6.26	261.05	26,375	40.34	61.63	56,774	39.74	142.82
1967	23,703	5.74	388.46	27,024	37.38	66.63	44,777	24.04	186.16
1968	17,369	4.55	369.70	38,709	42.38	87.76	88,121	36.21	243.26
1969	21,873	3.42	615.82	34,280	34.06	96.79	62,717	26.87	233.29
1970	15,220	2.90	488.50	34,104	39.23	82.04	42,624	22.23	191.67
1971	10,186	2.02	475.34	22,701	29.99	71.66	43,907	19.91	220.48
1972	11,735	2.46	453.96	18,143	31.56	54.61	40,013	18.04	221.66
1973	22,305	9.23	232.66	14,955	36.15	39.41	40,486	22.69	178.35
1974	28,250	4.44	615.72	26,448	33.69	75.51	36,545	14.14	258.26
1975	11,205	4.55	225.16	38,359	22.71	164.39	43,833	13.82	317.04
1976	14,937	3.87	361.52	28,246	25.12	108.42	39,421	14.54	271.01

Table 11.--Estimated total catch (MT) relative abundance (kg/100 hooks) and effective effort (10⁶ hooks) for Indian Ocean billfishes.

Year	Blue marlin			Striped marlin			Black marlin			Swordfish			Sailfish		
	Catch (MT)	Abundance index (kg/100 hooks)	Effective effort (10 ⁶ hooks)	Catch (MT)	Abundance index (kg/100 hooks)	Effective effort (10 ⁶ hooks)	Catch (MT)	Abundance index (kg/100 hooks)	Effective effort (10 ⁶ hooks)	Catch (MT)	Abundance index (kg/100 hooks)	Effective effort (10 ⁶ hooks)	Catch (MT)	Abundance index (kg/100 hooks)	Effective effort (10 ⁶ hooks)
1952	800	49.35	1.62	100	5.60	1.78	300	8.99	3.34						
1953	2,000	23.86	8.40	300	4.24	7.10	800	9.17	8.72						
1954	3,300	16.78	19.70	800	5.23	15.32	1,100	10.11	10.87	200	1.38		200	1.90	3.90
1955	3,600	14.21	25.38	780	4.42	17.66	1,080	11.10	9.72	240	2.06		180	1.41	2.29
1956	4,980	10.58	47.17	1,740	3.99	43.72	1,500	7.87	19.06	480	2.00		300	0.97	1.84
1957	3,800	9.09	41.87	1,800	3.36	53.64	1,400	6.29	22.24	300	1.30		300	1.61	1.84
1958	4,100	11.07	37.09	1,700	3.56	47.89	1,200	9.57	12.31	500	1.72	1.47	400	1.90	0.92
1959	4,300	8.94	48.17	2,100	4.26	49.38	1,200	6.83	17.56	500	1.15	2.10	500	3.07	1.84
1960	3,700	6.17	60.06	2,000	2.70	74.19	1,700	5.93	28.64	600	1.36	1.40	500	2.29	2.98
1961	3,200	5.07	63.28	2,400	2.39	100.82	1,400	4.50	31.14	700	1.26	1.33	500	2.63	1.84
1962	3,100	5.08	61.10	1,800	2.24	80.53	1,800	5.17	34.81	900	1.17	1.12	800	2.34	3.90
1963	2,634	3.84	68.63	1,783	2.01	88.93	1,451	4.50	32.27	1,051	1.22	1.40	675	1.70	2.52
1964	3,740	4.32	86.66	1,886	1.85	102.09	1,654	4.23	39.13	1,254	1.10	1.40	777	1.51	1.84
1965	3,878	2.95	131.53	3,335	2.45	136.61	1,344	3.42	39.33	1,344	1.22	1.05	1,222	2.73	3.21
1966	3,754	2.84	132.51	4,163	1.92	216.80	1,391	4.09	34.00	1,391	1.24	1.12	1,296	2.24	3.21
1967	4,074	2.59	157.54	4,463	1.34	334.90	1,548	3.64	42.50	1,831	1.46	1.05	1,972	3.12	3.90
1968	4,036	2.26	178.85	3,436	1.55	226.58	2,460	4.18	58.83	1,971	1.32	0.91	1,630	2.34	2.98
1969	3,875	1.86	208.19	4,729	1.31	361.45	2,339	4.27	54.76	2,284	1.35	1.33	1,187	1.80	3.67
1970	3,038	1.72	177.35	3,110	1.00	313.06	1,845	2.65	69.55	2,255	1.25	1.40	1,016	3.17	3.90
1971	2,532	2.03	124.97	2,092	0.94	222.82	1,435	3.24	44.33	1,583	1.10	1.61	1,349	2.63	3.44
1972	2,509	2.82	89.08	1,511	0.79	191.88	893	1.89	47.29	1,554	1.62	1.96	1,145	2.87	4.36
1973	1,891	3.28	57.69	1,117	1.03	108.48	709	1.93	36.67	1,148	1.05	1.12	429	2.09	5.05
1974	2,370	3.30	71.94	2,800	1.31	214.01	1,342	1.98	67.83	1,771	1.32	0.84	652	2.09	4.59
1975	2,277	1.86	22.33	2,114	1.37	154.43	1,187	1.93	61.39	1,235	1.21	1.19	991	1.51	3.21
1976	1,515	1.88	80.68	3,401	1.92	177.13	476	1.75	27.14	1,069	1.26	1.12	601	2.39	5.28

Table 12.--Results of production model analyses for Indian Ocean albacore, bigeye tuna, and yellowfin tuna.

Smoothing period (yr)	Albacore				Yellowfin tuna				Bigeye tuna			
	$\hat{MSY}$ (MT)	$E_{opt}^{\wedge}$ (10^6 hooks)	$\hat{M}$	Fit index	$\hat{MSY}$ (MT)	$E_{opt}^{\wedge}$ (10^6 hooks)	$\hat{M}$	Fit index	$\hat{MSY}$ (MT)	$E_{opt}^{\wedge}$ (10^6 hooks)	$\hat{M}$	Fit index
1	16,199	86	0.39	0.8065	49,936	∞	0.0	0.9370	59,953	∞	0.0	0.6302
2	17,760	∞	0.0	1.1044	43,058	∞	0.0	1.0138	59,070	∞	0.0	1.0098
3	12,784	∞	0.0	1.0089	45,444	1,455	0.05	1.0019	32,490	452	1.20	1.0024
4	8,864	∞	0.0	1.0025	43,534	∞	0.0	1.0006	30,644	443	0.99	1.0009

Table 13.--Results of production model analyses for Indian Ocean blue marlin, striped marlin, and black marlin.

Smoothing period (yr)	Striped marlin				Blue marlin				Black marlin			
	$\hat{MSY}$ (MT)	$\hat{E}_{opt}$ (10^6 hooks)	$\hat{M}$	Fit index	$\hat{MSY}$ (MT)	$\hat{E}_{opt}$ (10^6 hooks)	$\hat{M}$	Fit index	$\hat{MSY}$ (MT)	$\hat{E}_{opt}$ (10^6 hooks)	$\hat{M}$	Fit index
1	3,215	449	0.10	1.0000	3,572	229	0.05	0.9774	1,526	173	0.75	1.0001
2	2,930	219	0.24	1.0128	3,652	71	0.62	1.0282	1,484	158	0.63	1.0001
3	3,557	∞	0.00	1.0022	3,527	77	0.63	1.0023	1,430	170	0.35	1.0000
4	3,153	607	0.07	1.0008	3,377	78	0.52	1.0008	1,397	217	0.17	1.0000

Table 14.--Percentage distribution of nominal effort (hooks) by Japanese longliners in the Indian Ocean, by latitude, 1952-76.

Year	Latitude																Effort (10 ³ hooks)
	20°-15°N	15°-10°N	10°-5°N	5°N-0°	0°-5°S	5°-10°S	10°-15°S	15°-20°S	20°-25°S	25°-30°S	30°-35°S	35°-40°S	40°-45°S	45°-50°S			
1952	0.0	0.0	0.0	0.0	28.14	39.34	30.13	2.39	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2,974	
1953	0.0	0.0	0.0	0.0	8.96	41.22	42.22	7.60	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8,437	
1954	0.0	5.11	11.87	3.56	22.02	26.68	25.35	4.07	1.34	0.0	0.0	0.0	0.0	0.0	0.0	13,783	
1955	0.0	0.31	2.65	10.69	34.75	29.60	20.46	0.56	0.89	0.09	0.0	0.0	0.0	0.0	0.0	29,626	
1956	0.0	1.06	2.35	9.99	26.01	30.69	26.52	2.92	0.45	0.01	0.0	0.0	0.0	0.0	0.0	51,959	
1957	0.53	3.74	8.08	10.90	11.48	27.86	29.17	7.96	0.28	0.0	0.0	0.0	0.0	0.0	0.0	28,023	
1958	3.95	7.03	11.48	11.69	9.63	17.19	24.24	7.75	5.72	1.32	0.0	0.0	0.0	0.0	0.0	24,573	
1959	1.11	4.28	6.06	10.28	10.78	8.49	13.74	13.91	16.93	14.36	0.06	0.0	0.0	0.0	0.0	34,944	
1960	0.02	1.55	3.57	8.73	13.67	12.69	17.95	8.69	7.02	25.47	0.63	0.01	0.0	0.0	0.0	54,237	
1961	0.52	1.53	3.73	6.31	8.17	13.80	18.26	12.09	16.17	19.31	0.11	0.0	0.0	0.0	0.0	60,027	
1962	0.19	0.46	1.69	7.78	17.24	22.03	13.37	7.60	6.49	17.99	4.98	0.18	0.0	0.0	0.0	68,093	
1963	0.24	0.99	2.32	2.54	7.02	17.86	13.23	10.73	8.47	31.22	4.97	0.41	0.0	0.0	0.0	57,420	
1964	0.05	0.65	2.30	3.95	6.37	20.59	16.66	7.21	4.40	29.53	7.90	0.39	0.0	0.0	0.0	68,872	
1965	0.89	1.35	5.92	11.48	12.18	17.08	11.50	7.14	4.28	21.20	6.03	0.90	0.04	0.01	0.01	79,848	
1966	0.18	3.77	6.74	9.40	15.27	17.09	11.84	3.64	4.51	15.76	4.17	0.96	1.80	4.87	4.87	89,566	
1967	1.23	3.98	9.20	7.44	8.20	11.19	9.89	4.17	2.19	7.01	10.47	8.14	13.40	3.48	3.48	126,305	
1968	0.13	0.65	1.10	5.78	10.08	17.92	9.78	4.77	1.16	3.41	8.53	9.04	15.57	12.08	12.08	118,557	
1969	0.78	4.77	6.78	9.68	7.77	5.30	4.81	3.28	1.48	2.74	6.37	20.14	20.92	5.18	5.18	101,107	
1970	1.56	2.82	3.55	2.57	4.27	13.51	5.75	4.56	1.22	5.82	7.36	12.98	22.27	11.76	11.76	78,170	
1971	0.77	1.17	4.51	4.43	9.35	8.63	2.06	1.79	1.39	3.29	10.54	11.71	19.16	21.20	21.20	88,598	
1972	0.48	1.29	10.28	7.95	3.77	5.75	1.93	0.74	0.38	1.06	1.78	12.74	25.95	25.90	25.90	72,105	
1973	0.49	0.67	3.68	2.01	2.86	4.00	1.83	1.05	0.60	2.26	2.53	19.73	35.52	22.77	22.77	79,326	
1974	0.11	1.32	2.06	3.69	3.91	7.52	4.24	2.21	1.61	2.97	4.19	14.39	33.90	17.88	17.88	85,617	
1975	0.35	1.07	2.89	2.68	4.79	8.75	5.90	1.92	1.09	1.79	3.68	16.81	33.71	14.57	14.57	91,207	
1976	0.74	0.97	1.72	0.85	1.64	1.77	2.61	0.55	0.48	0.67	1.61	19.23	45.90	21.26	21.26	79,914	

CODE 507

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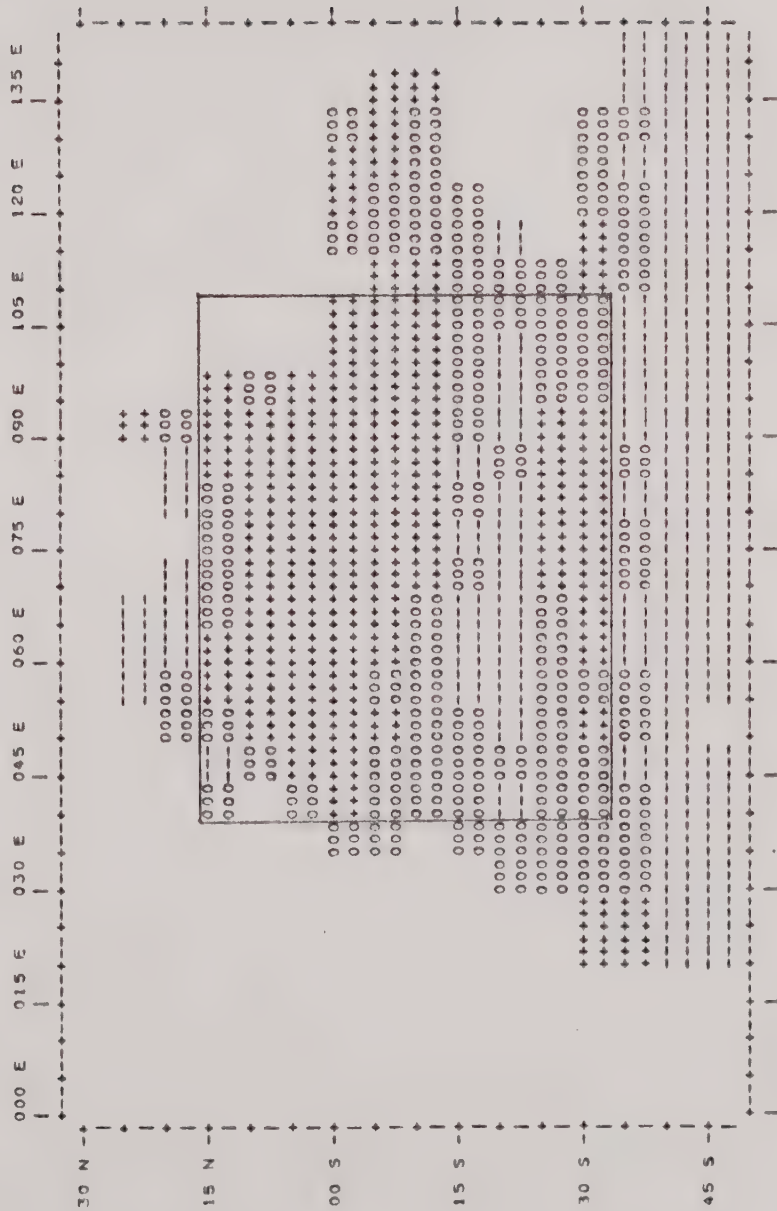
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Figure 1.--Distribution of average catch per hook for albacore caught by Japanese longliners in the Indian Ocean, 1952-76. Index area outlined.

LONGLINE STATISTICS BY LOCATION
 FAR SEAS FISHERIES RESEARCH LABORATORY DATA (X55973)
 CPUE - AVERAGE OF RATIOS - HOOKS

CODE 507

SPECIES: BIGEYE NATION: JAPAN YEAR: ALL PERIOD: ALL



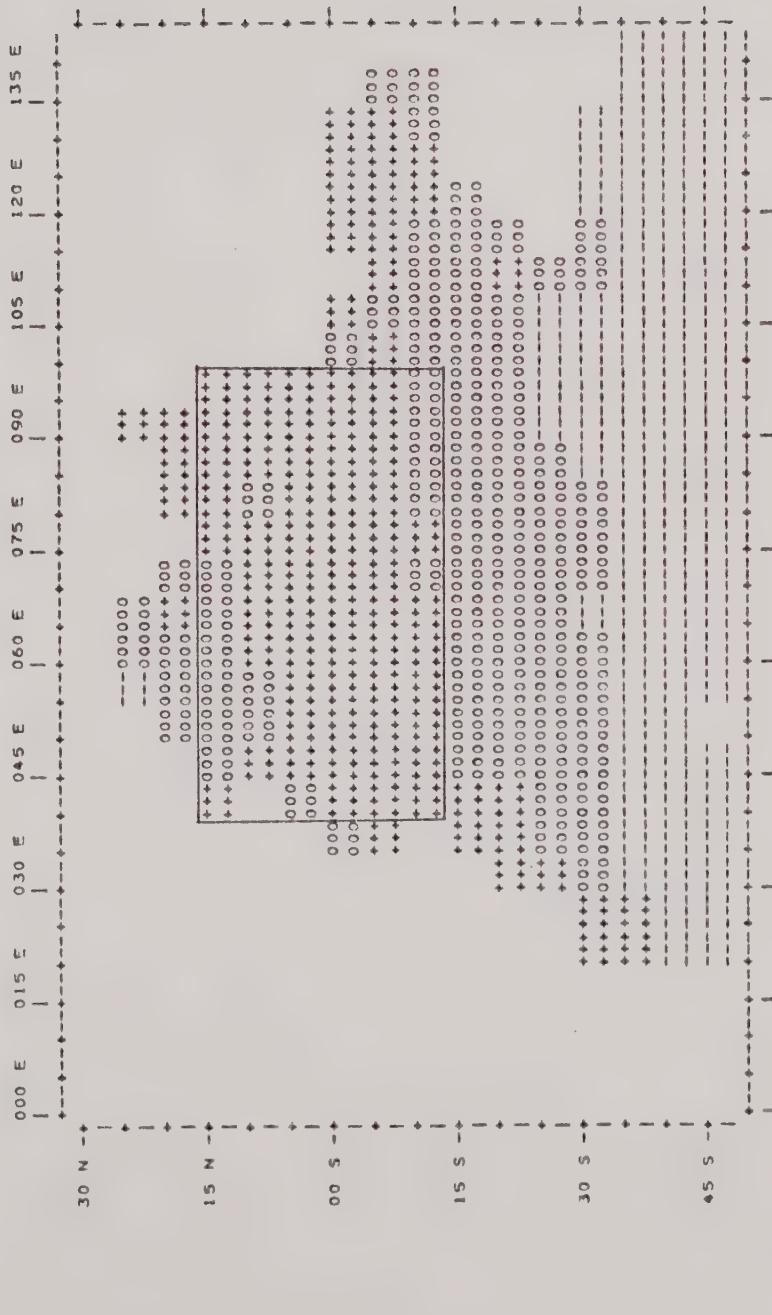
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Figure 2.--Distribution of average catch per hook for bigeye tuna caught by Japanese longliners in the Indian Ocean, 1952-76. Index area outlined.

LONGLINE STATISTICS BY LOCATION
 FAR SEAS FISHERIES RESEARCH LABORATORY DATA (X55973)
 CPUE - AVERAGE OF RATIOS - HOOKS

CODE 507

SPECIES: YELLOWFIN NATION: JAPAN YEAR: ALL PERIOD: ALL



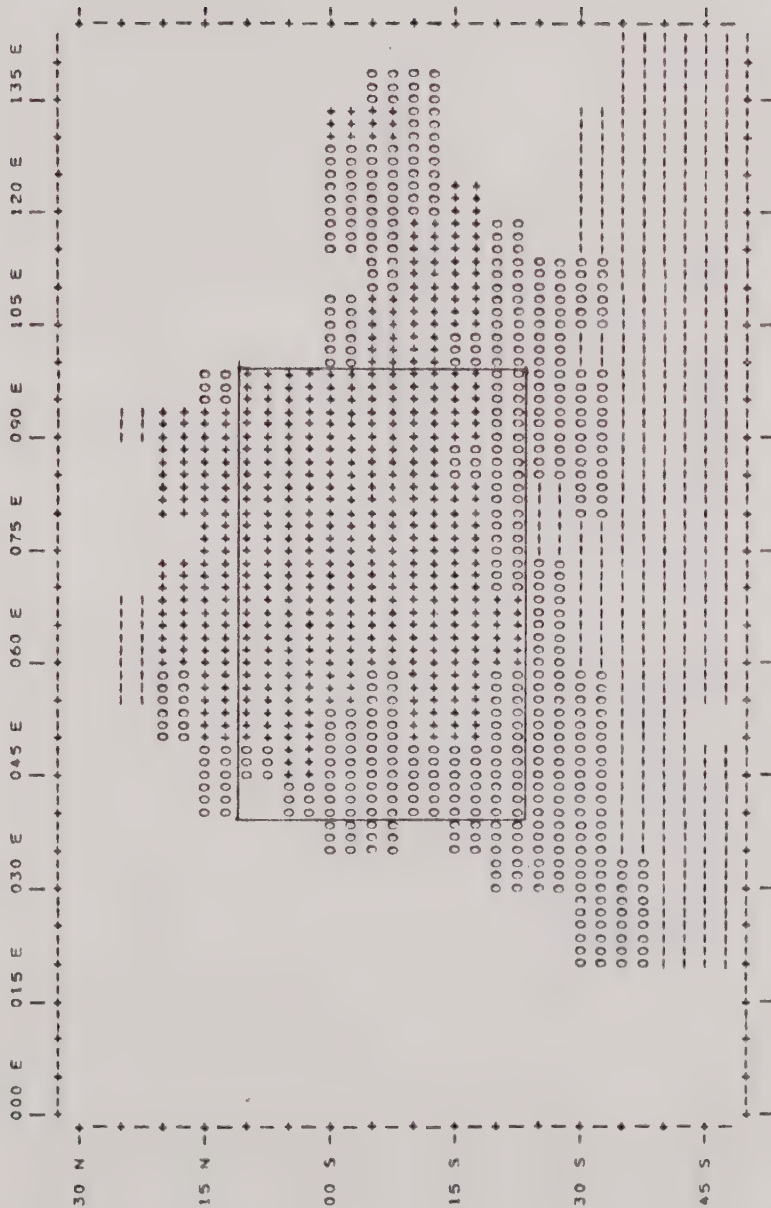
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Figure 3.--Distribution of average catch per hook for yellowfin tuna caught by Japanese longliners in the Indian Ocean, 1952-76. Index area outlined.

LONGLINE STATISTICS BY LOCATION
 FAR SEAS FISHERIES RESEARCH LABORATORY DATA (X55973)
 CPUE - AVERAGE OF RATIOS - HOOKS

CODE 507

SPECIES: BLUE MARLIN NATION: JAPAN YEAR: ALL PERIOD: ALL



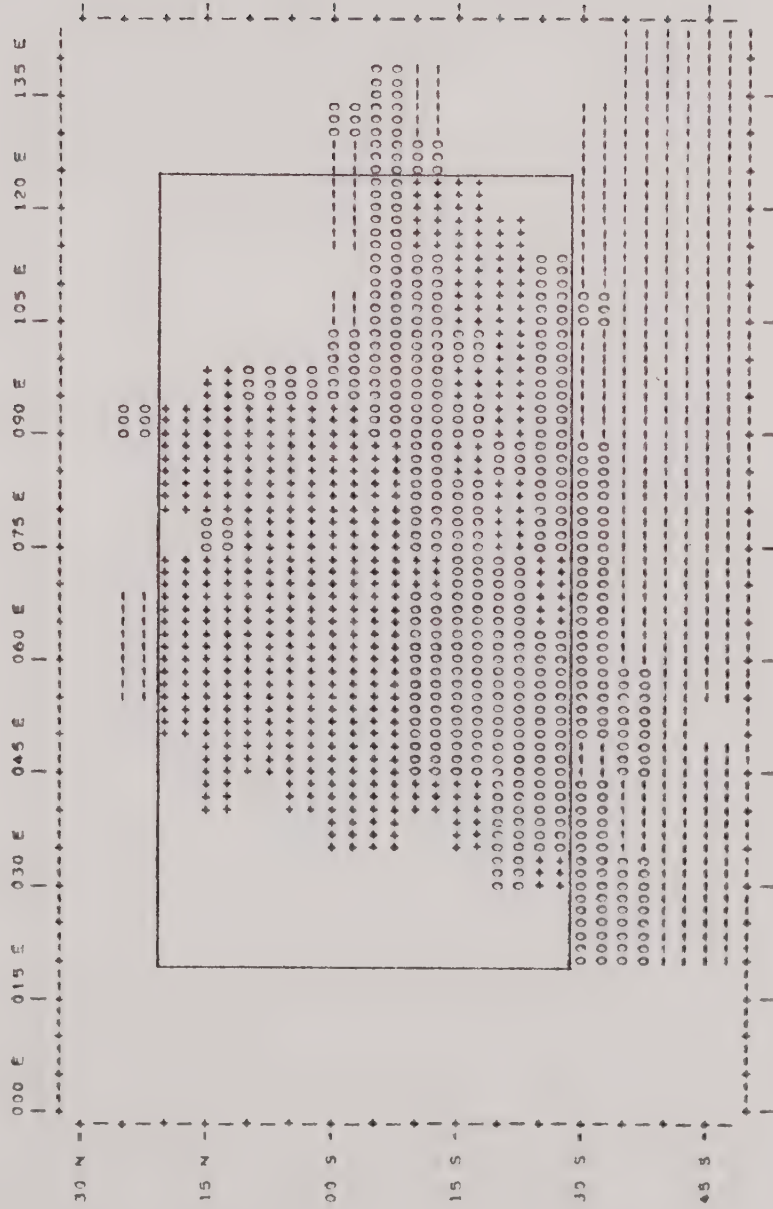
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Figure 4.--Distribution of average catch per hook for blue marlin caught by Japanese longliners in the Indian Ocean, 1952-76. Index area outlined.

LONGLINE STATISTICS BY LOCATION
 FAR SEAS FISHERIES RESEARCH LABORATORY DATA (X55973)
 CPUE - AVERAGE OF RATIOS - HOOKS

CODE 507

SPECIES: STRIPED MARLIN NATION: JAPAN YEAR: ALL PERIOD: ALL



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Figure 5.--Distribution of average catch per hook for striped marlin caught by Japanese longliners in the Indian Ocean, 1952-76. Index area outlined.

LONGLINE STATISTICS BY LOCATION
 FAR SEAS FISHERIES RESEARCH LABORATORY DATA (X55973)
 CPUE - AVERAGE OF RATIOS - HOOKS

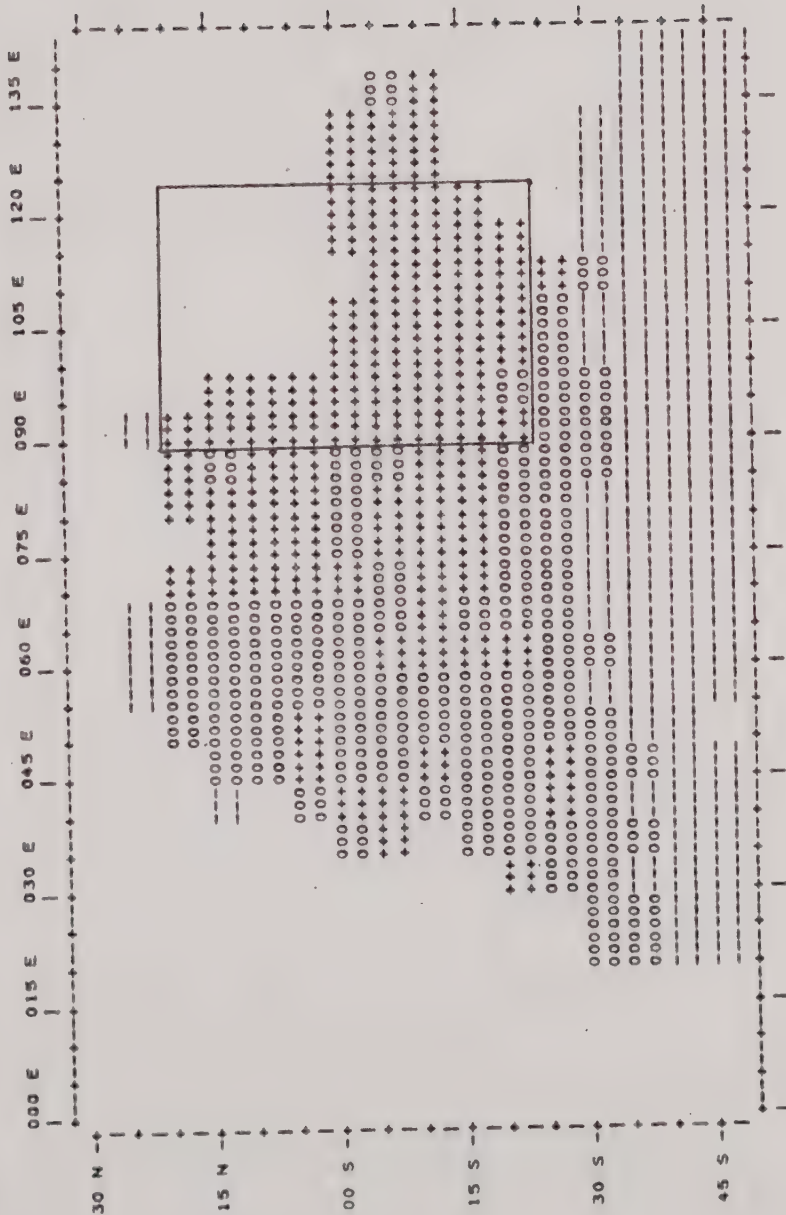
CODE 507

PERIOD: ALL

YEAR: ALL

NATION: JAPAN

SPECIES: BLACK MARLIN



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 --- TO +103E-04 000 TO +367E-03 *** TO +676E-02

Figure 6.--Distribution of average catch per hook for black marlin caught by Japanese longliners in the Indian Ocean, 1952-76. Index area outlined.

CODE 807

--	FROM	.000E+00	000	FROM	.202E-03	++	FROM	.381E-03
--	TO	.202E-03	000	TO	.381E-03	++	TO	.209E-02

Figure 7.--Distribution of average catch per hook for swordfish caught by Japanese longliners in the Indian Ocean, 1952-76. Index areas outlined.

LONGLINE STATISTICS BY LOCATION
 FAR SEAS FISHERIES RESEARCH LABORATORY DATA (X55973)
 CPUE - AVERAGE OF RATIOS - HOOKS

CODE 507

SPECIES: OTHER GILLFISHES NATION: JAPAN YEAR: ALL PERIOD: ALL



--- FROM .000E+00 000 FROM .109E-04 *** FROM .483E-03
 --- TO .109E-04 000 TO .483E-03 *** TO .561E-02

Figure 8.--Distribution of average catch per hook for sailfin caught by Japanese longliners in the Indian Ocean, 1952-76. Index areas outlined.

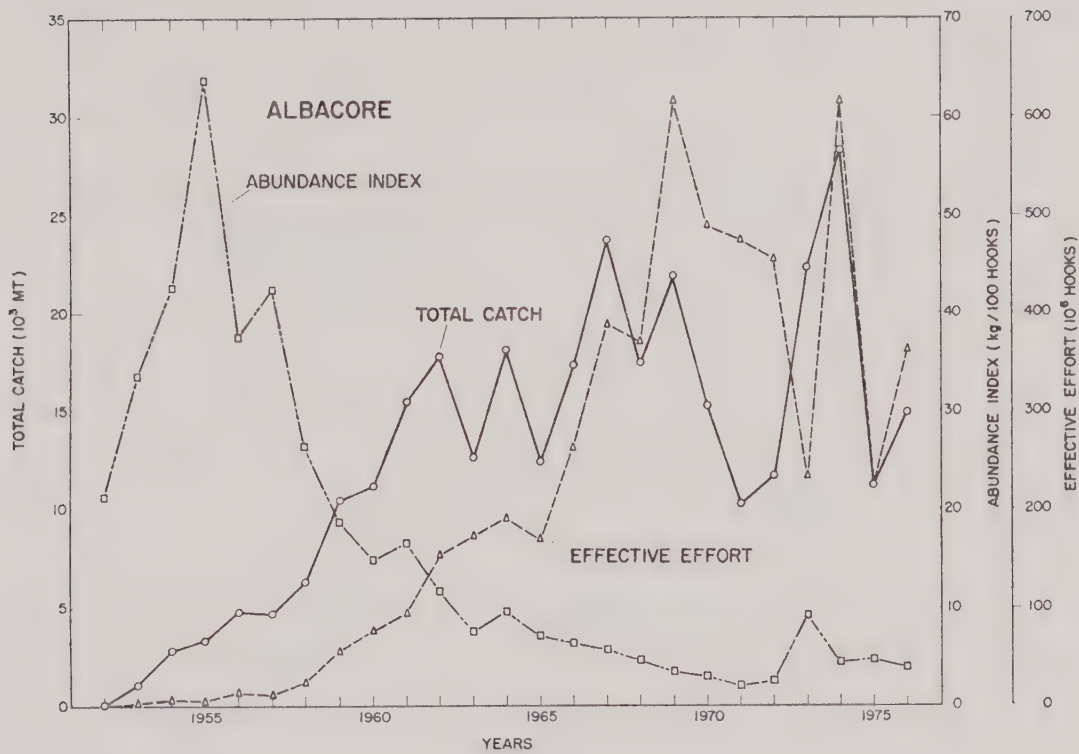


Figure 9:--Estimated total catch (10^3 MT), relative abundance (kg/100 hooks), and effective effort (10^6 hooks) for Indian Ocean albacore.

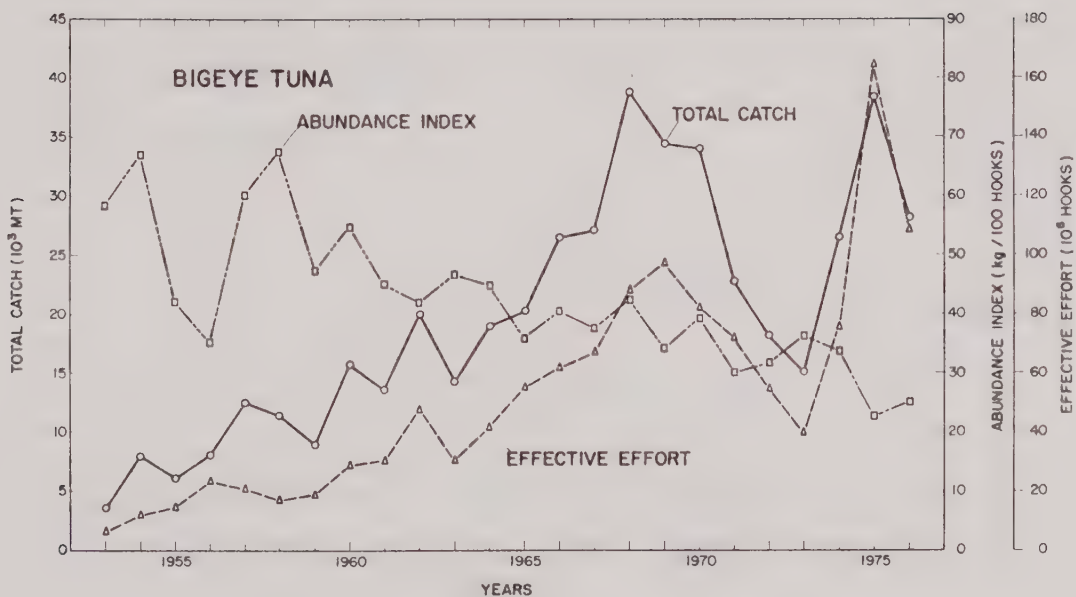


Figure 10.--Estimated total catch (10^3 MT), relative abundance (kg/100 hooks), and effective effort (10^6 hooks) for Indian Ocean bigeye tuna.

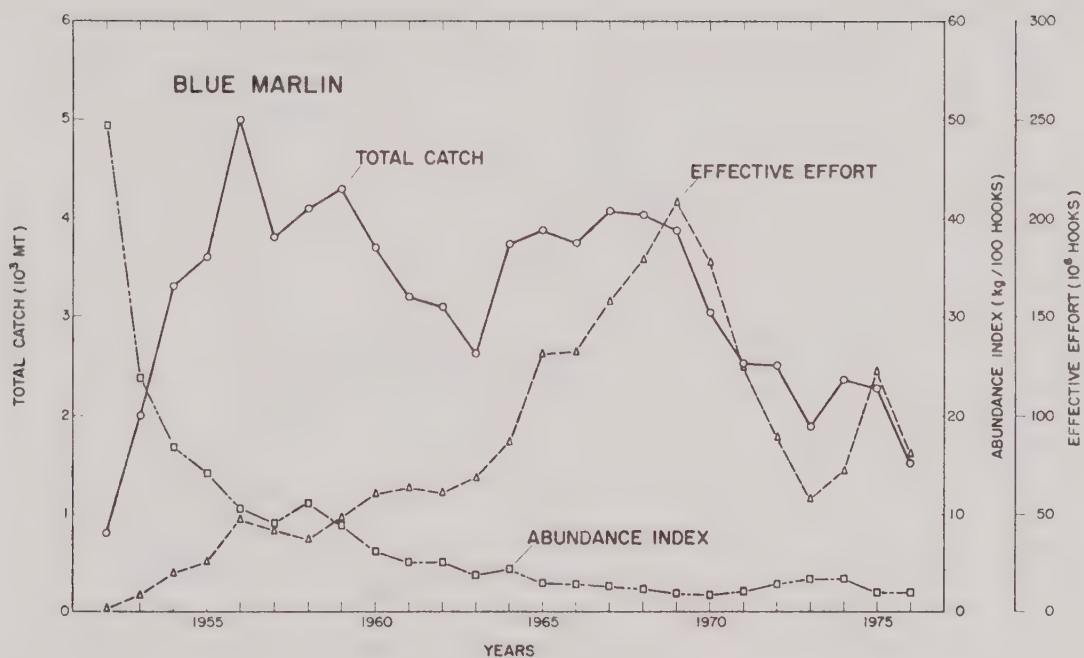


Figure 12.--Estimated total catch (10^3 MT), relative abundance (kg/100 hooks), and effective effort (10^6 hooks) for Indian Ocean blue marlin.

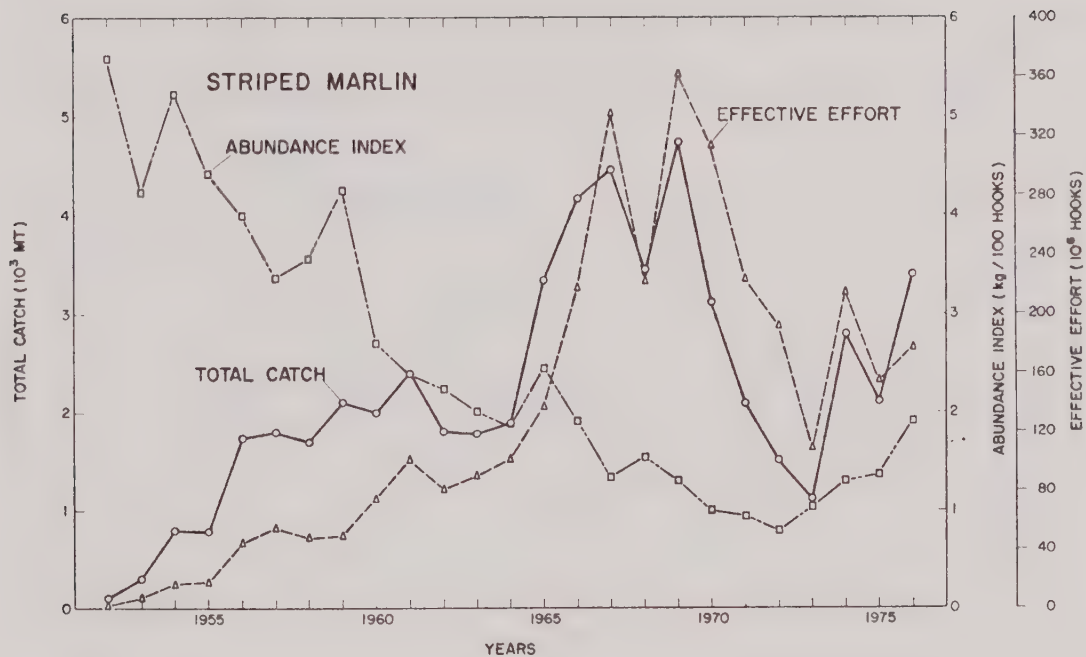


Figure 13.--Estimated total catch (10^3 MT), relative abundance (kg/100 hooks), and effective effort (10^6 hooks) for Indian Ocean striped marlin.

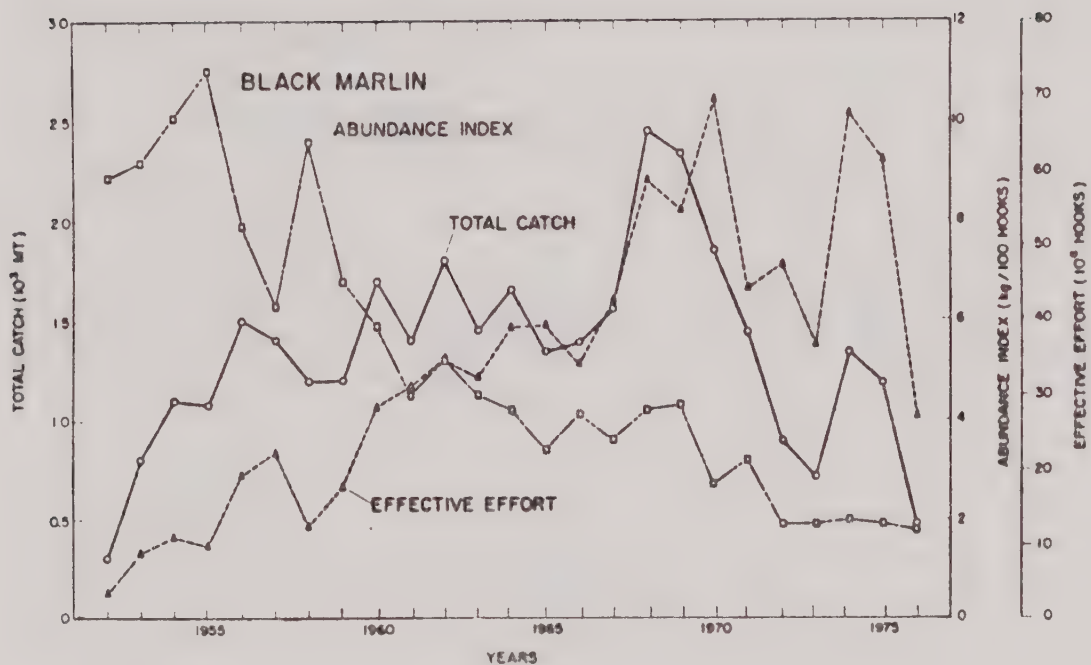


Figure 14.--Estimated total catch (10^3 MT), relative abundance (kg/100 hooks), and effective effort (10^6 hooks) for Indian Ocean black marlin.

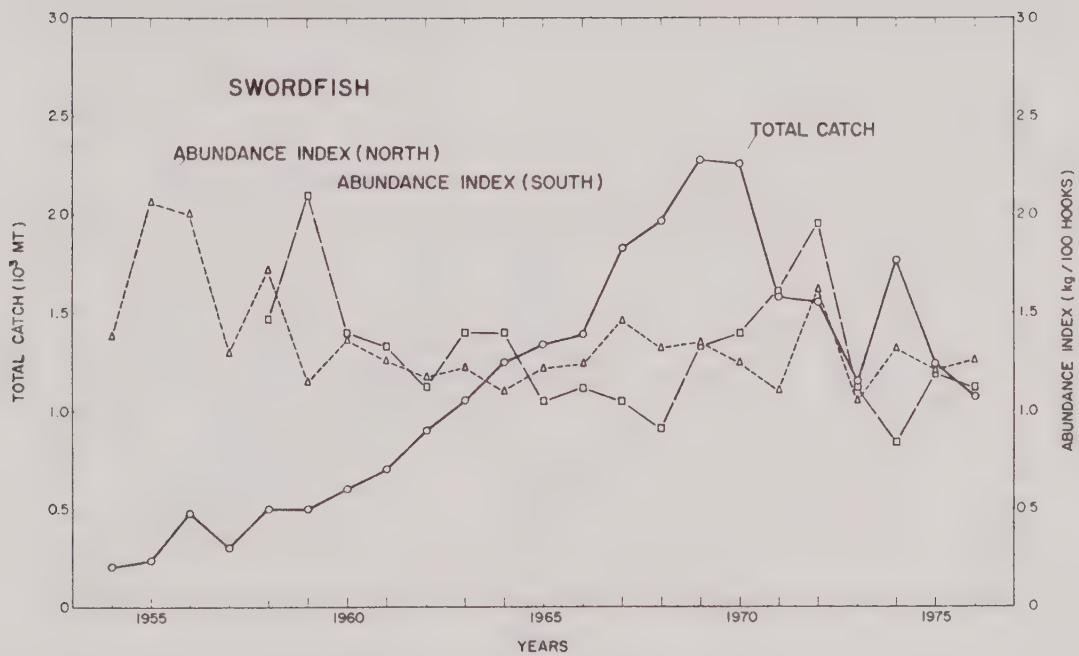


Figure 15.--Estimated total catch (10^3 MT) and relative abundance (kg/100 hooks) for Indian Ocean swordfish. Abundance indices are given for two index areas.

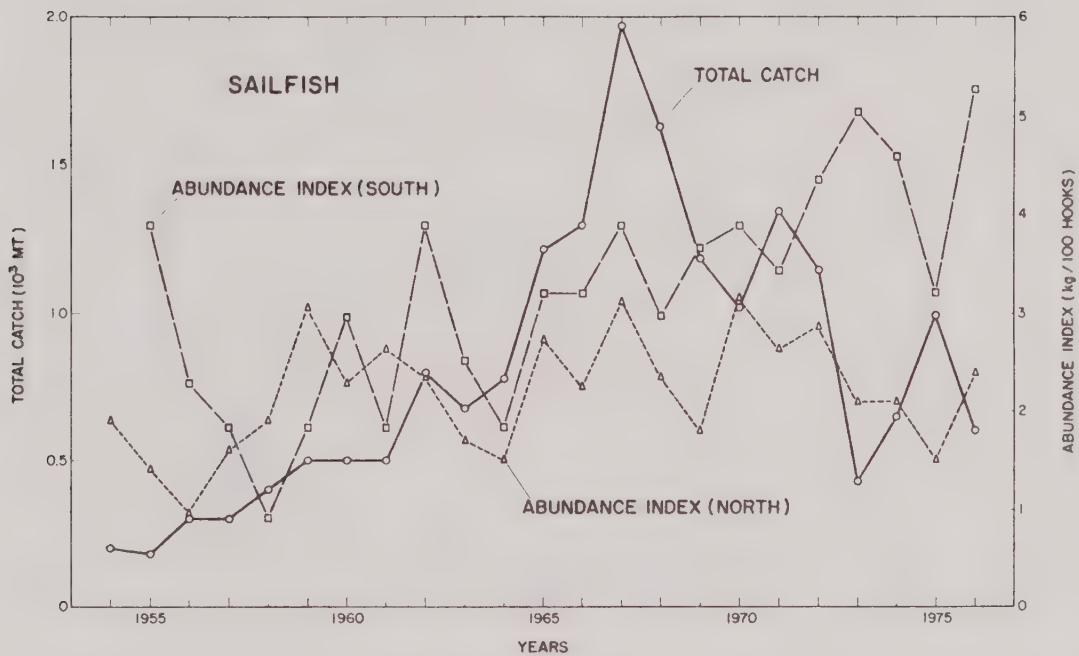


Figure 16.--Estimated total catch (10^3 MT) and relative abundance (kg/100 hooks) for Indian Ocean sailfish. Abundance indices are given for two index areas.

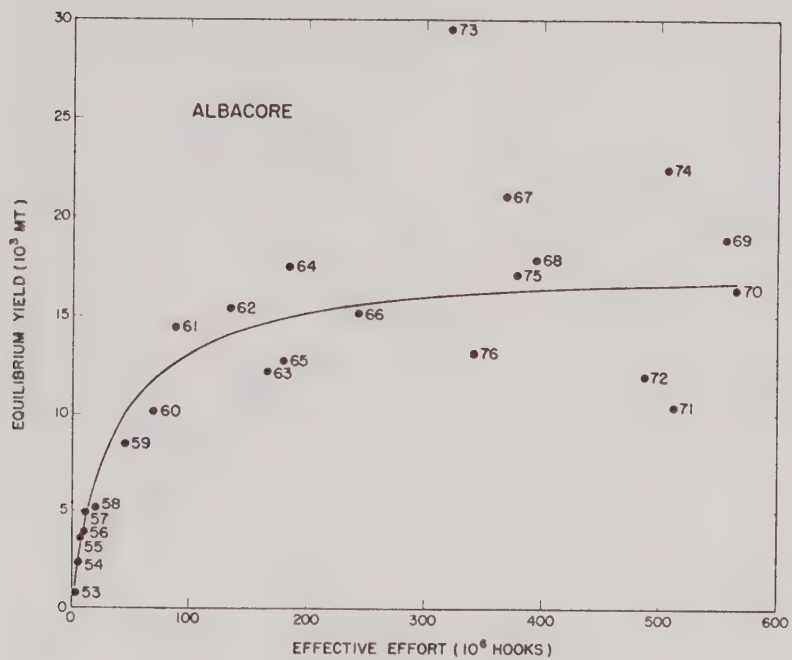


Figure 17.--Predicted relationship between equilibrium yield (10^3 MT) and effective effort (10^6 hooks) for Indian Ocean albacore, based on production model analysis.

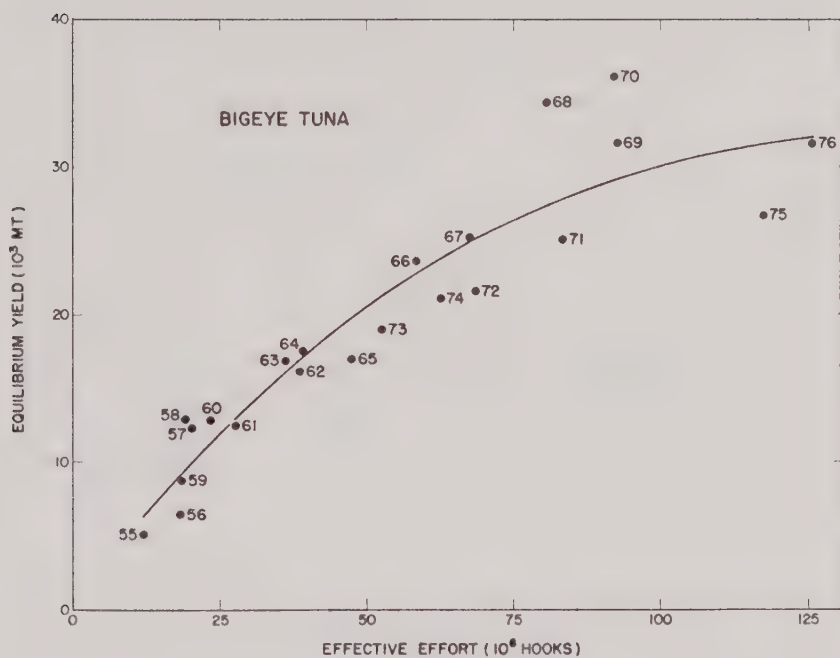


Figure 18.--Predicted relationship between equilibrium yield (10^3 MT) and effective effort (10^6 hooks) for Indian Ocean bigeye tuna, based on production model analysis.

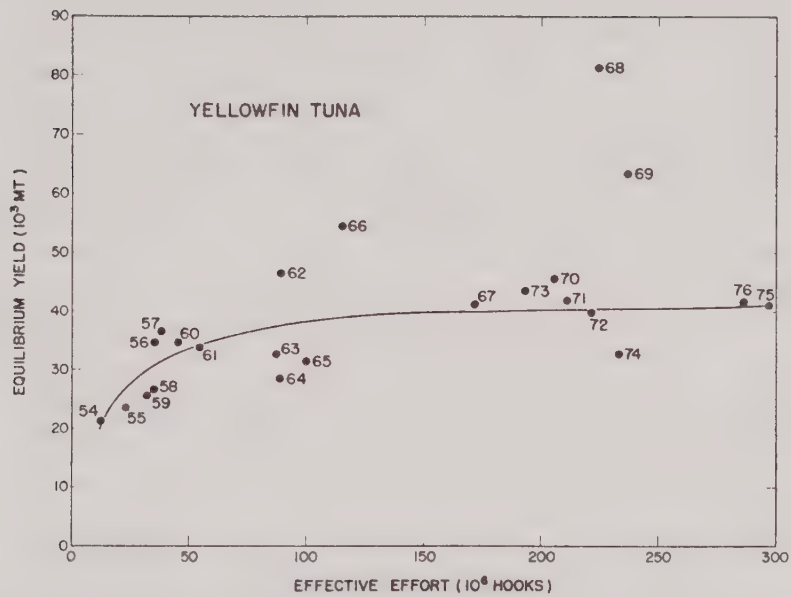


Figure 19.--Predicted relationship between equilibrium yield (10^3 MT) and effective effort (10^6 hooks) for Indian Ocean yellowfin tuna, based on production model analysis.

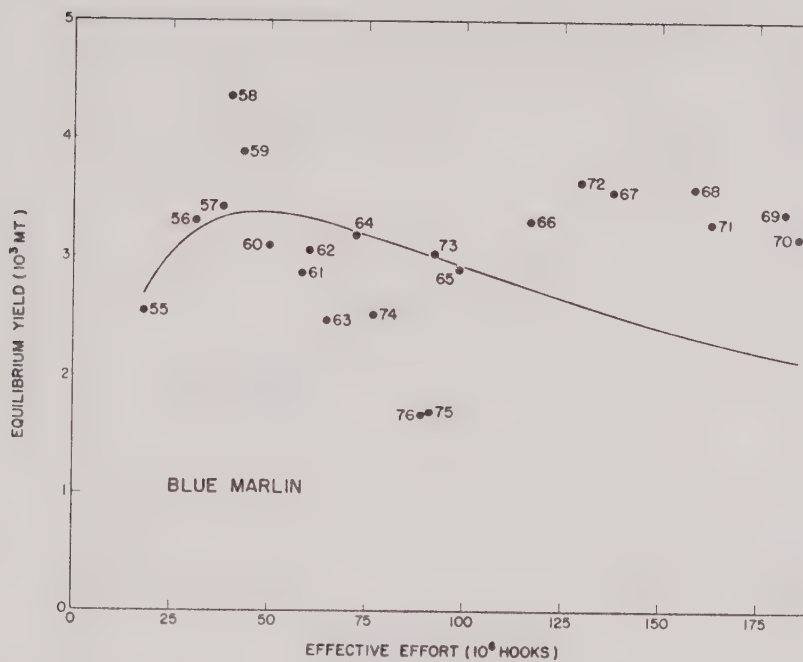


Figure 20.--Predicted relationship between equilibrium yield (10^3 MT) and effective effort (10^6 hooks) for Indian Ocean blue marlin, based on production model analysis.

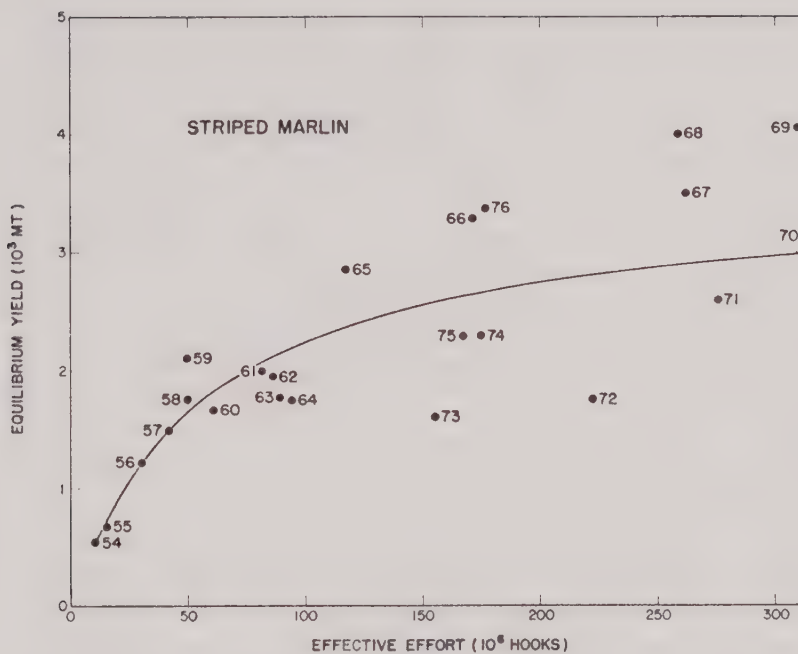


Figure 21.--Predicted relationship between equilibrium yield (10^3 MT) and effective effort (10^6 hooks) for Indian Ocean striped marlin, based on production model analysis.

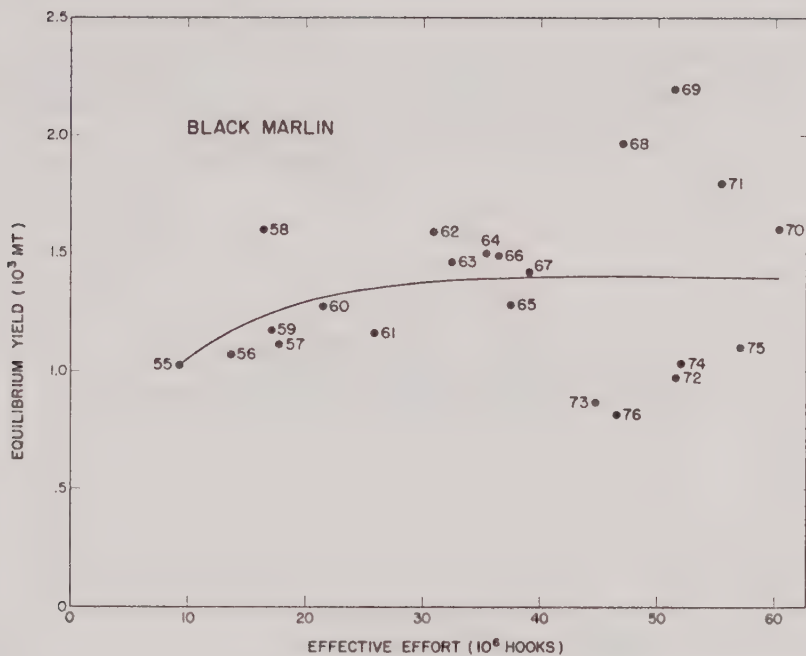


Figure 22.--Predicted relationship between equilibrium yield (10^3 MT) and effective effort (10^6 hooks) for Indian Ocean black marlin, based on production model analysis.

COMPILATION OF PUBLISHED ESTIMATES OF TUNA LIFE HISTORY
AND POPULATION DYNAMICS PARAMETERS

Howard O. Yoshida
Southwest Fisheries Center
National Marine Fisheries Service, NOAA
Honolulu, Hawaii 96812

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This working paper was prepared solely for discussions at the Workshop on the Assessment of Selected Tuna and Billfish Stocks in the Indian and Pacific Oceans (Shimizu, Japan, 13-22 June 1979) and is subject to revision. Its contents should not be cited without consent of the author.

Stock assessment studies require estimates of (1) certain factors that cause changes to the stock and (2) other life history parameters. The purpose of this paper is to compile such data, specifically, published estimates of von Bertalanffy growth parameters, instantaneous mortality coefficients, length-weight relations, fecundity, and size at sexual maturity of tunas including albacore, Thunnus alalunga; bigeye tuna, T. obesus; northern bluefin tuna, T. thynnus; southern bluefin tuna, T. maccoyii; and yellowfin tuna, T. albacares.

Because of the commercial importance of tunas, there is now a large accumulation of information on the biology of these species; however, the data available on each individual species were not equal in volume and information on some species were not as plentiful. Although a rigid set of criteria was not followed in compiling the data, generally, more recent data and those data that appeared "reasonable," in light of available biological information on the various species, were selected for inclusion.

LENGTH-WEIGHT RELATIONS

Numerous length-weight relations of albacore, bigeye, northern bluefin, southern bluefin, and yellowfin tunas in the form, $W = aL^b$, where W is weight in kilograms, L is length in centimeters, and a and b are estimated parameters are available (Tables 1-5). In many of the equations computed by the various authors, the length and weight units used varied. For ease of comparison, all the equations that required it were recomputed in terms of kilograms and centimeters.

Many of the predictive regressions that have traditionally been used to relate length and weight in fishes are in some degree inherently biased (Beauchamp and Olson 1973; Ricker 1973). Ricker (1973) pointed out that a functional regression is more appropriate even for the purpose of prediction and Beauchamp

and Olson (1973) noted that the logarithmic transformation to linearize data used by many investigators introduces an inherent bias. As far as I know all the length-weight relations in Tables 1-5 are uncorrected predictive regressions except that for the South Pacific albacore computed by Yong.¹

VON BERTALANFFY GROWTH PARAMETERS

Estimates of von Bertalanffy growth parameters for the five species of tunas reported on here are numerous in the literature (Tables 6-10). These estimates are available from growth studies based on scale, otolith, and vertebra reading methods, tagging experiments, size-frequency analyses, and varying combinations of the different methods. The growth parameters were either estimated by the original author or by other investigators using data available in the literature (e.g. Shomura 1966).

L_{∞} estimates for albacore (Table 6) range from 104.8 to 146.3 cm. These estimates can be compared to the observed maximum size of albacore, 120-124 cm reported in the literature (Otsu 1960; Miyake and Hayasi 1978). Murphy (1977) stated that L_{∞} is an estimate of the mean maximum size and that "therefore the largest observed fish should be at least slightly larger than the estimated mean maximum size, if the growth equation is to be regarded as realistic." Using this criterion of the reasonableness of the L_{∞} estimates, any estimate greater than about 124 cm for albacore would be unreasonable or unrealistic.

Estimates of L_{∞} for bigeye tuna range from 183.0 to 338.53 cm (Table 7) as compared to observed maximum sizes of 190-198 cm (Shomura 1966; Miyake and Hayasi 1978). For northern bluefin tuna L_{∞} estimates range from 277.3 to 437.46 (Table 8); the observed maximum size is over 300 cm (Miyake and Hayasi 1978). The L_{∞} estimates for southern bluefin tuna are 180.8 to 222.5 cm and the maximum observed size 188 to 230 cm (Murphy 1977; Miyake and Hayasi 1978),

and for yellowfin tuna, 150-307.9 cm (Table 10) and 190 cm (Miyake and Hayasi 1978), respectively.

INSTANTANEOUS MORTALITY COEFFICIENTS

Estimates of instantaneous mortality coefficients (M = natural, F = fishing, Z = total) are available in varying numbers for all the tuna species under consideration (Table 11). It appears that more estimates of mortality rates are available for albacore and yellowfin tuna than for other tunas. However, some available estimates in the literature may have been overlooked.

Murphy and Sakagawa (1977) made a review and evaluation of available estimates of tuna natural mortality rates. The two criteria they used to make their evaluations were (1) how closely the assumptions needed to derive the estimates were met and (2) whether the estimates agreed with other estimates available for the same species. When comparable mortality estimates were unavailable or few, they used the axiom that long-lived species have low natural mortality rates and short-lived species relatively high mortality rates in making their evaluation. They concluded that the most reasonable estimates of M for albacore were between 0.2 and 0.4; for bigeye tuna, in the lower portion of the range 0.35 to 0.73; northern bluefin tuna, 0.1 and 0.2; and yellowfin tuna around 0.8.

FECUNDITY AND SEXUAL MATURITY

Estimates of fecundity are available for all the tunas under consideration (Table 12). However, as far as I could determine, size at first spawning information for northern bluefin and southern bluefin tunas was unavailable in the literature. Baglin (1976) indicated that there still are questions on the actual age of maturity of northern bluefin tuna in the Atlantic.

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TEXT FOOTNOTE

1. M. Y. Y. Yong. Southwest Fisheries Center Honolulu Laboratory,
National Marine Fisheries Service, NOAA, Honolulu, HI 96812. Pers.
commun., May 1979.

Table 1.--Length-weight relations ($W = aL^b$) of albacore. Length (L) is in centimeters and weight (W) in kilograms.

Area	Size range (cm)	a	b	Source	Comments
Eastern Pacific	50.0-85.0	1.225×10^{-5}	3.13	Partlo (1955)	
	38.0-100.0	2.188×10^{-5}	2.99	Clemens (1961)	
Hawaii and North Pacific	49.6-127.6	2.5955×10^{-5}	2.9495	Nakamura and Uchiyama (1966)	
American Samoa (landed)	78.0-108.0	8.8406×10^{-5}	2.6822	Nakamura and Uchiyama (1966)	
North Atlantic	44.0-112.0	6.303×10^{-6}	3.2825	Beardsley (1971)	
South Pacific	--	1.7401×10^{-5}	3.0521	Yong ¹	Males. Functional regression (see Ricker 1973).
	--	1.4168×10^{-5}	3.0967	Yong ¹	Females. Functional regression (see Ricker 1973).
South Africa	--	2.3079×10^{-5}	2.98	de Jaeger (1963)	Males.
	--	1.40343×10^{-5}	3.09	de Jaeger (1963)	Females.
Western North Pacific	45-85	1.781×10^{-5}	3.053	Lee et al. (1978)	

¹See text footnote 1.

Table 2.--Length-weight relations ($W = aL^b$) of bigeye tuna. Length (L) is in centimeters and weight (W) in kilograms.

Area	Size range (cm)	a	b	Source	Comments
Central Pacific	80.0-190.0	3.661×10^{-5}	2.90182	Nakamura and Uchiyama (1966)	
West Africa	41.0-132.0	1.2494×10^{-5}	3.12082	Lenarz (1974)	
South Africa	--	8.24277×10^{-5}	2.72	de Jaeger (1963)	Males.
	--	5.8106×10^{-5}	2.79	de Jaeger (1963)	Females.
Eastern Atlantic (off Ivory Coast)	86.2-179.2	4.454×10^{-6}	3.31768	Choo (1976)	
Western North Pacific	45.5-163.8	1.97308×10^{-5}	3.024669	Morita (1973)	
Central and eastern Pacific	65.5-173.0	1.97927×10^{-5}	3.021632	Morita (1973)	
Atlantic Ocean	50.2-175.5	2.50577×10^{-5}	2.973242	Morita (1973)	
Indian Ocean	73.5-166.5	4.92194×10^{-5}	2.832860	Morita (1973)	

Table 3.--Length-weight relations ($W = aL^b$) of northern bluefin tuna. Length (L) is in centimeters and weight (W) in kilograms.

Area	Size range (cm)	a	b	Source	Comments
Western Atlantic	--	3.17×10^{-5}	2.90444	Sakagawa and Coan (1974)	
Eastern Atlantic	25.0-279.5	1.9×10^{-5}	3.0	Rodríguez-Roda (1964)	May-June 1956-59.
	130.0-249.5	5.3×10^{-5}	2.8	Rodríguez-Roda (1964)	July-August 1956-59.
Eastern Pacific	55.8-178.4	5.686×10^{-5}	2.79012	Bell (1964)	
Western North Pacific	171.0-219.0	2.977×10^{-5}	2.910	Shingu et al. (1974)	
Western South Pacific	171.0-225.0	2.503×10^{-5}	2.9249	Shingu et al. (1974)	

Table 4.--Length-weight relations ($W = aL^b$) of southern bluefin tuna.

Length (L) is in centimeters and weight (W) in kilograms.

Area	Size range (cm)	a	b	Source
Australia	--	3.13087×10^{-5}	2.9058	Robins (1963)
Southeastern Indian Ocean	--	1.01625×10^{-5}	3.115	Shingu (1970)
Southwestern Pacific Ocean	--	9.4624×10^{-6}	3.120	Shingu (1970)

Table 5.--Length-weight relations ($W = aL^b$) of yellowfin tuna. Length (L) is in centimeters and weight (W) in kilograms.

Area	Size range (cm)	a	b	Source	Comments
Pacific coast of Costa Rica	54.2-157.1	2.3864×10^{-5}	2.940	Schaefer (1948)	
Eastern tropical Pacific	47.6-114.9	1.8496×10^{-5}	3.020	Chatwin (1959)	
Hawaii	--	2.8522×10^{-5}	2.9045	Tester and Nakamura (1957)	
Japan	--	6.64×10^{-6}	3.1878	Kamimura and Honma (1959)	Dressed weights of fish used.
Central Pacific	70.0-180.0	1.4769×10^{-5}	3.05834	Nakamura and Uchiyama (1966)	
West Africa	40.0-170.0	2.1804×10^{-5}	2.96989	Lenarz (1974)	
South Africa	--	8.1466×10^{-6}	3.18	de Jaeger (1963)	
	--	3.99165×10^{-5}	2.85	de Jaeger (1963)	
Eastern Atlantic (off Ivory Coast)	104.5-163.0	3.5133×10^{-6}	3.3432	Choo (1976)	
Western South Pacific	26.0-157.0	2.51211×10^{-5}	2.939597	Morita (1973)	
Eastern and central Pacific	63.4-148.0	3.49515×10^{-5}	2.868069	Morita (1973)	
Atlantic Ocean	46.9-169.5	1.6612×10^{-5}	3.026546	Morita (1973)	
Indian Ocean	79.5-162.5	6.5874×10^{-5}	2.750437	Morita (1973)	

Table 6.--Von Bertalanffy growth parameter estimates for albacore. K and t_0 are in years.

Area and fishing gear	Investigator(s)	Method	Growth parameters			Comments
			L_∞ (cm)	K	t_0	
Pacific coast of Japan	Uno (1936)	Vertebra reading	104.8	0.431	1.504	Growth parameters computed by Shomura (1966).
North Pacific	Nose et al. (1957)	Scale reading (1952-53 samples)	114.4	0.308	0.818	Do.
	Nose et al. (1957)	Scale reading (1953-54 samples)	145.3	0.159	-0.056	Do.
	Bell (1962)	Scale reading	108.8	0.2247	-2.2728	Growth parameters computed by author.
Eastern North Pacific; troll	Yabuta and Yukinawa (1963)	Scale reading	146.3	0.150	-0.396	Growth parameters computed by Shomura (1966).
North Pacific; long-line, pole and line, troll	Otsu (1960)	Tagging	118.8	0.250	1.999	Do.
North Pacific; troll, pole and line, rod and reel, longline	Clemens (1961)	Tagging	135.6	0.17	1.87	Growth parameters computed by author.
Atlantic; longline and surface	Beardsley (1971)	Length-frequency analysis	140.0	0.141	-1.63	Do.
Atlantic	Yang (1970)	--	135.0	0.19	--	Do.
North Atlantic; troll	Bard (1974)	Scale reading, length-frequency analysis	134.4	0.183	-0.35	Do.

Table 7.---Von Bertalanffy growth parameter estimates for bigeye tuna. K and t_0 are in years.

Area and fishing gear	Investigator(s)	Method	Growth parameters			Comments
			L_∞ (cm)	K	t_0	
Western North Pacific (north of lat. 25°N, west of 180°)	Yukinawa and Yabuta (1963)	Length-frequency analysis	257.5	0.156	-0.107	Growth parameters com- puted by Shomura (1966).
Pacific (north of lat. 10°S)	Yukinawa and Yabuta (1963)	Scale reading	215	0.208	0.00055	Growth parameters com- puted by authors.
	Yukinawa and Yabuta (1963)	Scale reading	213.1	0.212	0.017	Growth parameters com- puted by Shomura (1966).
Central Pacific (Hawaii); longline	Shomura and Keala (1963)	Length-frequency analysis (males)	196.7	0.267	-0.929	Growth parameters com- puted by authors.
	Shomura and Keala (1963)	Length-frequency analysis (females)	183.0	0.316	0.718	Do.
Eastern Pacific (east of long. 130°W, lat. 10°N-25°S)	Kume and Joseph (1966)	Length-frequency analysis	186.95	0.38	0.528	Do.
Pacific (north of lat. 10°S)	Nose et al. (1957)	Scale reading	195.2	0.16	-1.128	Growth parameters com- puted by Shomura (1966).
Eastern Atlantic (Dakar-Pointe-Noire)	Champagnat and Pianet (1974)	Length-frequency analysis	338.53	0.104	-0.542	Growth parameters com- puted by authors.

Table 8.--Von Bertalanffy growth parameter estimates for northern bluefin tuna. K and t_0 are in years.

Area and fishing gear	Investigator(s)	Method	Growth parameters			Comments
			L_∞ (cm)	K	t_0	
Southern Spain; traps	Rodríguez-Roda (1971)	Vertebra reading	355.84	0.09	0.89	Growth parameters computed by author.
Western North Atlantic	Mather and Jones ¹	---	447.88	0.053	-1.592	Growth parameters computed by Sakagawa and Coan (1974).
	Butler et al. (1977)	Otolith reading	286.64	0.134	0.3278	Males. Growth parameters computed by authors.
	Butler et al. (1977)	Otolith reading	277.315	0.116	0.7999	Females. Growth parameters computed by authors.
Western North Atlantic; pound nets, hook and line	Mather and Schuck (1960)	Length-frequency scale-vertebra reading	437.46	0.055	-1.489	Growth parameters computed by Sakagawa and Coan (1974).
Western Pacific	Yukinawa and Yabuta (1967)	Scale reading and length-frequency analysis	320.5	0.1035	-0.7034	Growth parameters computed by authors.

¹Mather, F. J. III, and A. C. Jones. 1972. A preliminary review of the stock structure of bluefin tuna in the Atlantic Ocean. Unpubl. manuscript, 18 p. Woods Hole Oceanographic Institution, Woods Hole, MA 02543.

Table 9.--Von Bertalanffy growth parameter estimates for southern bluefin tuna. K and t_0 are in years.

Area and fishing gear	Investigator(s)	Method	Growth parameters			Comments
			L_∞ (cm)	K	t_0	
Southwest Pacific-Southeast Indian Ocean; longline and pole and line	Yukinawa (1970)	Scale reading	219.7	0.135	0.04	Growth parameters computed by author.
South Australia; pole and line	Murphy (1977)	Tagging	180.84	0.146	-0.011	Do.
Australian waters; pole and line and trolling	Shingu (1970)	Length-frequency analysis	222.5	0.14	0.011	Growth parameters computed by author based on data from Robins (1963).
Southwest Pacific-Southeast Indian Ocean; pole and line, trolling, longline	Shingu (1970)	Tagging	187.4	0.149	0.021	Growth parameters computed by author based on Australian and Japanese tagging data.

Table 10.--Von Bertalanffy growth parameter estimates for yellowfin tuna. K and t_0 are in years.

Area and fishing gear	Investigator(s)	Growth parameters			Comments
		L_∞ (cm)	K	t_0	
Pacific coast of Japan; longline and pole and line	Yabuta and Yukinawa (1957)	168.9, 168	0.564; 0.55	0.368, 0.35	Growth parameters computed by Shomura (1966) and Suzuki (1971), respectively.
Western Pacific (lat. 12°N-5°S, long. 130°E-180°); longline	Yabuta et al. (1960)	197.5, 190; 188.4	0.312, 0.33, 0.32	-1.030, 0	Growth parameters computed by Shomura (1966), Suzuki (1971), and Le Guen and Sakagawa (1973), respectively.
	Yabuta et al. (1960)	191.1	0.327	-1.020	Growth parameters computed by Shomura (1966) using estimated lengths derived from Walford transformation of scale data.
Central Pacific (Hawaii); mainly longline	Moore (1951)	190.2, 192, 191.9	0.454, 0.44, 0.43	0.267, 0.22	Growth parameters computed by Shomura (1966), Suzuki (1971), and Le Guen and Sakagawa (1973), respectively.
Western Pacific (lat. 12°N-5°S, long. 130°E-180°); longline	Yabuta and Yukinawa (1957)	151.6, 150	0.663, 0.66	-0.620, 0.40	Growth parameters computed by Shomura (1966) and Suzuki (1971).
Eastern Pacific; mainly pole and line	Hennemuth (1961)	169, 200.3	0.60, 0.36	0.83, 0.47	Growth parameters computed by author and Le Guen and Sakagawa (1973), respectively.
Eastern Pacific; pole and line and purse seine	Davidoff (1963)	167, 200.3	0.60, 0.36	0.83	Do.
Eastern Pacific (north of lat. 10°N); pole and line	Diaz (1963)	165.6	0.71	--	Growth parameters computed by author.
	Diaz (1963)	214.3	0.36	--	Do.
Eastern Pacific; pole-and-line	Diaz (1963)	167.2	0.65	--	Do.
	Diaz (1963)	179.8	0.49	--	Do.
Western Pacific (0° to lat. 10°N, long. 155°-175°E); longline	Yang et al. (1969)	195.2	0.36	--	Do.

Table 10.--Continued.

Area and fishing gear	Investigator(s)	Method	Growth parameters			Comments
			L _∞ (cm)	K	t ₀	
Atlantic (lat. 39.5°N-6°S, long. 83°W-6°E); longline	Yang et al. (1969)	Scale reading	222.8, 223.0	0.28, 0.23	--	Growth parameters computed by author and Le Guen and Sakagawa (1973), respectively.
Eastern Atlantic						
Dakar	Le Guen et al. (1969)	Length-frequency analysis	206.6	0.3144	0.45	Growth parameters computed by authors.
Pointe-Noire	Le Guen et al. (1969)	Length-frequency analysis	182.4	0.4428	0.54	Do.
All areas	Le Guen et al. (1969)	Length-frequency analysis	191.7	0.3828	0.52	Do.
Eastern Atlantic; pole and line and purse seine						
Abidjan	Le Guen and Sakagawa (1973)	Length-frequency analysis (age unknown)	185.0	0.52	--	Do.
Dakar	Le Guen and Sakagawa (1973)	Length-frequency analysis (age unknown)	307.9	0.20	--	Do.
Gulf of Guinea	Le Guen and Sakagawa (1973)	Length-frequency analysis (age unknown)	185.0	0.49	--	Do.
Pointe-Noire	Le Guen and Sakagawa (1973)	Length-frequency analysis (age unknown)	210.1	0.32	--	Do.
All areas	Le Guen and Sakagawa (1973)	Length-frequency analysis (age unknown)	194.8	0.42	0.62	Do.
Eastern Atlantic (São Tomé-Angola); pole and line and purse seine	Le Guen and Sakagawa (1973)	Length-frequency analysis (age known)	175.2	0.53	0.80	Do.
Eastern Atlantic; pole and line	Baudin-Laurencin (1968)	Length-frequency analysis	218.5	0.2952	--	Do.
Eastern Atlantic (Pointe-Noire)	Le Guen and Champagnat (1968)	Length-frequency analysis	165.8, 166.5	0.5568, 0.5418	--	Do.
Eastern Atlantic (Dakar)	Le Guen and Champagnat (1968)	Length-frequency analysis	182.3	0.4308	--	Do.

Table 11.--Estimates of instantaneous mortality coefficients for tunas.

M = natural, F = fishing, and Z = total.

Species	Area	Instantaneous mortality coefficient			Source
		M	F	Z	
Albacore	Atlantic Ocean	0-0.30	--	--	Bard (1974)
	Atlantic Ocean	0.20, 0.32	--	0.96, 0.50, 0.79	Beardsley (1971)
	Pacific Ocean	--	--	0.4	Suda (1963)
	Pacific Ocean	0.2	--	--	Suda (1966)
	South Atlantic Ocean	0.475	--	0.805	Morita (1977)
	Indian Ocean	0.4-0.6	--	--	Suda (1974)
Bigeye tuna	Atlantic Ocean	0.23	--	--	Murphy and Sakagawa (1977)
	Indian Ocean	0.7268	--	1.130	Suda (1970)
	Pacific Ocean	0.349, 0.350, 0.5630	--	--	Ishii (1968)
	Pacific Ocean	0.10	--	0.4	Silliman (1966)
	Pacific Ocean	0.361	--	--	Suda and Kume (1967)
Bluefin tuna	Atlantic Ocean	0.10-0.20	0.28-1.00	0.59-1.75	Mather et al. (1974)
	Atlantic Ocean	0.1-0.2	--	0.48-2.96	Sakagawa and Coan (1974)
	Atlantic Ocean	0.10	--	--	Murphy and Sakagawa (1977)

Table 11.--Continued.

Species	Area	Instantaneous mortality coefficient				Source
		M	F	Z		
Southern bluefin tuna	Indian-Pacific Oceans	0.2	--	--		Murphy (1977)
	Indian-Pacific Oceans	0.2-1.0	0+-2.61	1.15-1.84		Hayasi et al. (1972)
	Indian-Pacific Oceans	0.15, 0.16, 0.18	--	--		Suda (1971)
Yellowfin tuna	Atlantic Ocean	1.58, 2.61	--	--		Pianet and LeHir (1971)
	Pacific Ocean	0.11-4.57	0.56-2.02	0.77-5.17		Fink (1965)
	Pacific Ocean	0.64-0.90	0.82-1.08	1.60-1.85		Hennemuth (1961)
	Pacific Ocean	1.1, 2.5	--	--		Honma et al. (1971)
	Pacific Ocean	0.34, 0.44, 0.91	--	--		Ishii (1969)
	Pacific Ocean	0.55-1.05	0.69-1.20	--		Schaefer (1967)
	Pacific Ocean	0.3-0.8	--	--		Hayasi and Honma (1971)
Indian Ocean		0.35-0.44	--	--		Kawakami and Kitahara (1964) as cited by Suda (1971)
	Atlantic Ocean	0.80	--	--		Murphy and Sakagawa (1977)

Table 12.--Estimates of tuna fecundity and size at first spawning.

Species	Area	Size at first spawning	Number of ova per spawning	Source
Albacore	Central Pacific Ocean	90 cm (33 lb)	1-2 million	Otsu and Uchida (1959)
	Central South Pacific Ocean	86 cm	--	Otsu and Hansen (1962)
	Indian Ocean	--	1.8-1.9 million	Ueyanagi (1955)
	Western Pacific	90 cm	0.8-2.6 million	Ueyanagi (1957)
Yellowfin tuna	Central equatorial Pacific Ocean	70 cm	--	Yuen and June (1957)
	Hawaii	--	2-8 million	June (1953)
	Eastern Pacific Ocean	--	0.6-5.5 million	Joseph (1963)
	Eastern Pacific Ocean	50-60 cm	--	Schaefer and Orange (1956)
Bigeye tuna	Pacific Ocean	14-20 kg	2.9-6.3 million	Yuen (1955)
	Western Pacific	90-100 cm	--	Kikawa (1953)
	Indian Ocean	92 cm	--	Kume (1962)
	Western Atlantic	--	16.7-33.0 million	Baglin (1976)
Northern bluefin tuna				
Southern bluefin tuna	Indian Ocean	--	14.0-15.0 million	Kikawa (1964)

GUIDELINES FOR THE OPERATION OF THE
RESEARCH VESSEL KAAHELE'ALE

Donald C. Aasted
Southwest Fisheries Center
National Marine Fisheries Service, NOAA
Honolulu, Hawaii 96812

June 1979

I. DESCRIPTION OF BOAT

The RV Kahele'ale is a former U.S. Navy personnel boat that has been converted to a small fishery research vessel to be used in the nearshore waters around the Hawaiian Islands. The boat was acquired by the Southwest Fisheries Center, Honolulu Laboratory, to fulfill a need for a versatile vessel intended for trips of a relatively short duration and range, for which larger National Ocean Survey-operated vessels would not be suitable. The Kahele'ale is 33 ft long and has a fiber glass hull and a fiber glassed plywood pilothouse. Initially, the vessel is to be used for monitoring fish aggregation buoys and for tuna/billfish tracking, utilizing acoustic depth-sensing devices and a directional hydrophone installed in a sonar well.

II. SPECIFICATIONS

Name:	<u>Kahele'ale</u>
Hull:	Navy personnel boat, model 33MK3, built in 1965.
Construction:	Fiber glass
Length:	33 ft
Beam:	11 ft
Draft:	3 ft
<u>Power</u>	
Engine:	250 hp, General Motors 671, diesel model 6088M, with a 35 A alternator, 24 V dc starting system
Auxiliary:	7.5-kW Onan marine diesel generator with 12 V dc battery charging capacity, 12 V dc starting system
Battery charger:	110 V ac powered LEWCO 40 A, 12 V dc charging unit
Range:	200 mi
Speed:	11.5 kn
Fuel capacity:	240 gal (diesel)

Electronics

Radios (2): Motorola Nautilus 440 with all U.S. marine channels 25 W vhf
Regency 8-channel 12.5 W vhf

Fathometers (3): Apelco flasher/recorder, 0 to 540 ft
Coastal navigator digital sounder and depth alarm 2 to 99 ft/2 to 99 fathoms
Ross SL-600C straight line recorder 50 kHz, 0 to 900 ft

Radar: Decca 202, 24-mi range

Steering: Wagner hydraulic model N85

Autopilot: Benmar course setter 21, hydraulic

Compass: Airguide

Refrigeration: Ice chest

Accommodations: Two bunks

Emergency equipment

Radio	2
Emergency position indicating radio beacon (EPIRB)	1
Life jackets with ACR firefly rescue lights	6
Horseshoe life buoys with lights	2
Flare/signal kit	1
Searchlight	1
Medical kit	1
Fire extinguisher, 15-lb CO ₂	1

III. VESSEL OPERATOR CERTIFICATION PROCEDURES

A vessel operator will be certified by a memo signed by Donald C. Aasted, Small Vessel Supervisor (SVS), and Richard S. Shomura, Director, Honolulu Laboratory, after demonstrating a comprehensive knowledge of the operation of small boats by completing the Coast Guard Auxiliary examination or by submitting a record of documented prior experience of vessel operations. This knowledge or practical experience will include the following:

1. Seamanship
2. Rules of the road
3. Aids to navigation
4. Piloting
5. Operation of radios
6. Operation of radar
7. Operation of fathometers
8. Basic engineering (diesel) principles and procedures, specifically:
 - a. Analysis and correction of minor fuel, cooling, and electrical problems
 - b. Recognition of potential engine problems through use of gauges and audible, olfactory, and visual clues
 - c. Possession of a working knowledge of valves, bilge pumps, plumbing, and electrical systems
 - d. Ability to perform minor maintenance and repair tasks
9. Vessel handling skills:
 - a. Docking
 - b. Cruising
 - c. Heavy weather operations
 - d. Man overboard and other rescue operations
 - e. Anchoring situations--bottom and high seas

10. Operation of fire and lifesaving equipment

IV. PRE-CRUISE REQUIREMENTS AND OPERATIONS

A. Travel Orders

A blanket travel order has been issued to the Honolulu Laboratory covering all personnel anticipated to participate on trips aboard the vessel during FY-1979; additional personnel must be included on an addendum. If trips require reimbursement for per diem or meals, an additional Trip Authorization Form (42-5) must be filled out and submitted to the SVS prior to departure.

B. Vessel Scheduling

Vessel scheduling will be handled by the SVS. Requests for vessel time should be submitted in ample time before cruise dates to insure the readiness and availability of the vessel. A standard form cruise plan will be submitted to the SVS prior to departure and will include the following:

1. Personnel
2. Destination
3. Duration
4. Purpose
5. Special gear
6. Trip Authorization Form (if necessary)
7. Any additional information

C. Vessel Preparation

Prior to departure, the vessel operator will be required to check out the vessel and fill out a trip checkoff sheet. This sheet will be forwarded to the SVS together with the trip log upon completion of the trip. It is the responsibility of the vessel operator to work with the SVS to insure that the vessel is equipped and ready for sea.

V. OPERATIONS AT SEA

It is the responsibility of the vessel operator to ensure that the vessel is operated in a safe and prudent manner; therefore, while at sea, the operator will have final authority on all

aspects of vessel operation. If a significant deviation from the cruise plan occurs, it will be the responsibility of the vessel operator to notify the SVS via "radiocall" service.

The vessel operator will maintain a record of deck and radio operations including:

A. Deck Log

1. Trip number and date
2. Personnel list
3. Purpose
4. Destination
5. Date and time of:
 - a. Vessel departure
 - b. Engine start-up and shut down
 - c. Generator start-up and shut down
6. Activity--research or maintenance
7. Additions of fluids to engines or batteries
8. Deviations in gauge readings
9. Fuel filter reading at end of trip
10. Engine hours at the beginning and the end of a trip

B. Radio Log

1. Date and time
2. Channel
3. Purpose of call (brief)

VI. POST-CRUISE OPERATIONS

Upon completion of a trip the trip leader will submit a cruise report to the Director, Honolulu Laboratory, through the SVS, covering the highlights of the trip. This report will be submitted no later than 2 weeks after completion of the trip.

The vessel will be cleaned and all excess gear removed. The operator will submit the completed checkoff sheet and logs to the SVS.

VII. MISCELLANEOUS

The Director, Honolulu Laboratory and the SVS will have sole authority to authorize vessel operators.

The SVS will be responsible for the following:

1. Maintaining records and schedules
2. Managing the vessel reservation schedule
3. Maintaining a financial records system

The SVS will submit a monthly report of all vessel operations by the 25th of each month for inclusion in the Honolulu Laboratory's Monthly Narrative Report.

